Indicators and considerations for sustainable winter cereal production systems in the Overberg

by

Bianca Avril Stead

Thesis presented in partial fulfilment of the requirements for the degree of

Master of Science (Sustainable Agriculture)

at

Stellenbosch University

Department of Agricultural Economics, Faculty of AgriSciences

Supervisor: Dr Willem Hoffmann

Co-supervisor: Dr Johann Strauss

December 2021

Declaration

By submitting this thesis electronically, I declare that the entirety of the work contained therein is my own, original work, that I am the sole author thereof (save to the extent explicitly otherwise stated), that reproduction and publication thereof by Stellenbosch University will not infringe any third party rights and that I have not previously in its entirety or in part submitted it for obtaining any qualification.

Date: December 2021

Abstract

The world's population has been steadily increasing and is projected to reach 9.7 billion people in 2050. This necessitates a proportional increase in food production which will place increased pressure on natural resources which may lead to further environmental degradation. Therefore, there is an urgent need for more sustainable food production methods. Conservation agriculture (CA) has been put forward as one of the most holistic methods of sustainable agricultural intensification.

There are three main principles associated with CA, namely minimal or no-tillage, permanent organic soil cover and the use of crop rotations. This study was focused mainly on the crop rotation aspect of CA. The main objective for this study was to determine the extent to which identified critical drivers promote the long-term sustainability of different crop rotation systems for the Middle Rûens area of the Overberg. The most profitable crop rotation systems were identified and the physical and biological factors underpinning this profitability were discussed. This study focused only on short crop rotation systems although longer rotation systems are also used in the Overberg area.

This study used existing crop rotation trial data from Tygerhoek Experimental Farm in the Overberg which was managed according to CA principles. Four main rotation systems were considered, three of which consisted of a mix of cash crops and pastures, with one system having only cash crops. Wheat, barley and canola were the main cash crops focused on in this study. Data was collected from these trials from 2002 to 2020 and included climatic data, soil analysis data, all input costs, yields and prices of crops for each year as well as all livestock information. The data was separated into two main sections for analysis, namely the ecological data (yield and quality) and the economic data (gross margins and input costs).

The inclusion of pastures in crop rotation systems increased yields and thereby increased gross incomes for the specific systems. The system containing only cash crops had consistently lower yields and higher allocatable variable costs than the other three systems. This resulted in the systems including a pasture component having higher gross margins on average when compared to the continuous cash cropping system. Climatic conditions, cultivar choice and soil type were important determining factors when it came to both crop yield and quality. The resiliency of the systems to drought also improved over time as the yields recovered quickly after particularly dry years, such as 2019.

The three most substantial input costs for all systems were fertiliser, weed control and seed. Fertiliser costs were shown to decrease towards the end of the trial for the systems including pastures, but not for the cash cropping system. Weed control and seed costs were also higher in the continuous cash cropping system than in the other three systems. The total input costs for the systems including pastures also decreased towards the end of the trial, unlike those for the cash cropping system.

Profitability underpins the long-term sustainability of the short-rotation systems and understanding the drivers of this profitability is a necessity.

This thesis is dedicated to my parents, Miles and Denise Stead.

Acknowledgements

I wish to express my sincere gratitude and appreciation to the following persons and institutions:

- My parents, brother and sister for their unwavering support and encouragement in all my endeavors.

- Dr Willem Hoffmann, my supervisor, for his guidance throughout this process and for always being so friendly and willing to help.

- Dr Johann Strauss, my co-supervisor, for providing the data that made this project possible and for always being there to answer any and every question I may have had. His passion for conservation agriculture was very motivating.

- The Western Cape Agricultural Research Trust for the financial support that they provided which was a great help.

- The Department of Sustainable Agriculture for their financial support which was greatly appreciated.

- The staff members and students from the Department of Sustainable Agriculture who were always willing to assist in any way possible.

Table of Contents

List of Figures

List of Tables

List of Appendices

List of Abbreviations

CA: Conservation Agriculture

FAO: Food and Agriculture Organisation of the United Nations

SA: South Africa

ECAF: European Conservation Agriculture Federation

SOM: Soil Organic Matter

GDP: Gross Domestic Product

WCDA: Western Cape Department of Agriculture

DAFF: Department of Agriculture, Forestry and Fisheries

Ha: Hectares

EU: European Union

ARC: Agricultural Research Council

MT: Maize Trust

WCT: Winter Cereal Trust

CAWC: Conservation Agriculture Association of the Western Cape

GI: Gross Income

GM: Gross Margin

AVC: Allocatable Variable Cost

HLM: Hectolitre Mass

TT: Triazine Tolerant

Chapter 1 - Introduction

1.1) Background and Introduction

The world's population has been steadily increasing and is projected to increase further, from 7.7 billion people in 2020 to 9.7 billion in 2050 and 10.9 billion in 2100 (Gerland *et al.*, 2014; UN, 2020). The biggest increase in population size is anticipated to be in Africa. These population change projections indicate that food production will also have to increase proportionally to fulfil the growing demand. The population projections indicate that by 2050, food production would have to increase by 70% to meet the world's demand (Tilman & Clark, 2015). Increasing food production to this extent, however, will likely have a profoundly negative impact on the environment, mainly through pollution caused by chemicals associated with farming and the environmental degradation of the land used for food production purposes. There will also be increased competition between agricultural sectors, urban development and industrial growth for increasingly limited land and water resources. Agricultural production and land use change generate an estimated 25% of total greenhouse gas emissions from human activities (Bennetzen *et al*., 2016) and is a sector which will be directly affected by climate change. This pressurises the agricultural sector to adopt methods in which the world's natural resources will be used in a manner which is both sustainable and efficient over the long term (Knott, 2015).

A new approach to farming, which is growing in popularity, is Conservation Agriculture (CA), which is promoted as one of the most holistic approach to sustainable agriculture. Since the 1990's, CA has been rapidly adopted across the globe, to varying degrees across different continents (Derpsch & Friedrich, 2010). There are three main principles of conservation agriculture. These include: minimal tillage and soil disturbance; permanent organic soil cover and; diversified crop rotations (FAO, 2015). CA is not a "one size fits all" method; every farm and farmer is unique, with a unique set of ecological and social characteristics. Therefore, the principles of CA are merely guidelines by which the producer can build a foundation according to their unique farming environment. CA has been adopted to varying degrees throughout South Africa, with the Western Cape experiencing one of the highest adoption rates (Knott, 2015).

The Western Cape Province of South Africa has a typical Mediterranean climate and is a well-known winter cereal production area. Wheat is the primary field crop produced in the Western Cape. Before 1996, the Wheat Board acted as a form of protection for local wheat farmers by fixing producer prices on a production cost-plus basis which favoured producers under the protectionist government policy of food self-sufficiency (Hoffmann, 2010). This encouraged wheat farming in marginal areas to produce wheat under low-risk market conditions. Subsequently, there was a shift towards wheat monoculture in most grain production areas in South Africa. During 1996, however, the Wheat Board was abolished and producers were exposed to foreign markets and more volatile wheat prices and this caused many farmers to diversify crops as a counter measure to the increased risk (Hoffmann, 2001). This addition of new crop varieties in the wheat farming areas acted as a protagonist for crop rotations and the adoption of conservation agriculture in South Africa, particularly winter grain production region of the Western Cape.

The two main wheat production areas in the Western Cape are the Overberg and the Swartland. These two regions combined contribute 85% of the wheat produced in the Western Cape and employ approximately 27% of the agricultural workforce in the province (Hoffmann, 2010). Most farms in the area are rain-fed and there has been a high adoption rate of conservation agriculture principles, with crop rotations being a very prominent one. There are specific crops which could be incorporated into crop rotation systems in the Western Cape, particularly in the Overberg, due to the region’s moderate climate (Nell, 2019). Crops commonly incorporated into a crop rotation system with wheat include oats, barley, canola and lupine and various pasture crops. The move towards CA continues to grow in the Western Cape as it is seen as a more sustainable method of farming for the future.

1.2) Problem Statement and Research Question

There have been ongoing crop rotation trials running on Tygerhoek experimental farm, near Riviersonderend in the Overberg, since 2002. A conservation agriculture management approach was applied to all these trials. Whilst Tygerhoek focuses exclusively on short-rotations, it forms part of the larger main project with the two other research sites focusing on long-rotations. This thesis will only be looking at short-rotation data from Tygerhoek. The two principal reasons for initiating the larger main project were the following. Firstly, the lack of knowledge and understanding of both the short- and long-term crop rotation systems in the Overberg. Secondly, there was a lack of understanding of the mechanisms of both the internal and external economic and biological factors within these production systems, which support and underpin sustainable production. Knowledge gained from these trials could be used to improve the biological and financial sustainability of crop production systems in this area.

This project focuses on the factors that drive the long-term sustainability of different crop rotation systems in the Middle Rûens area. Data associated with these crop rotations has been recorded since 2002. Previous studies on these trials have been conducted and these include a financial analysis (Nell, 2019), soil profiling (Human, 2008) and a study on the livestock aspect of the farm (Cloete *et al.*, 2002). Although a financial analysis of the crop rotation trials has been done, there is still a need for the evaluation of identified critical physical, biological and ecological drivers of profitability for long-term sustainability within selected crop rotation systems in the Middle Rûens area.

The main research question for this project is: "To what extent do identified critical factors promote the long-term sustainability of different shorter term crop rotation systems in the Middle Rûens area of the Overberg?

1.3) Objectives

The main objective of this study is to determine the extent to which identified critical drivers promote the long-term sustainability of different crop rotation systems for the Middle Rûens area of the Overberg.

Within this main objective, the following specific research goals were identified:

1) To identify and describe the most profitable short rotation systems for the Middle Rûens area of the Overberg.

2) To determine which physical and biological factors underpin the profitability of each system, and

3) To evaluate the factors that drive the profitability of crop rotation systems.

1.4) Proposed Method of Study

This study used, as a point of departure, existing crop rotation trial data from Tygerhoek Experimental Farm. Crop trials are run by the Western Cape Department of Agriculture and are located near Riviersonderend in the Overberg. These trials aim to assess the potential of various crop rotation systems within a conservation farming framework. Tygerhoek is in a homogenous area known as the Middle Rûens which is a winter grain production area. The trials were started in 2002 and have been managed according to conservation agriculture principles with minimal soil disturbance and leftover crop residues following harvesting. Tygerhoek has the physical and biological characteristics of a typical farm in the Overberg. The data collected from these trials includes climatic data and soil profiles, all input costs, yields and prices of crops for each year as well as all livestock information. Various factors were isolated to identify the effects of factors such as precipitation, crop sequence and system response on yields, cost structure and profitability.

1.5) Layout of Study

Chapter 2 provides a comprehensive literature review, giving a more detailed background for the study. This will discuss the concept of CA, its origins and principles and will also look at both the benefits and constraints associated with the CA method of farm management. There will also be an overview of literature pertaining to winter cereal production in the Western Cape Province of South Africa, with particular focus on the Overberg region of the Western Cape which is where the study is based. A brief description of the global and local expansion of CA will also be given.

The materials and methods used for this study are discussed in Chapter 3. A detailed outline of trials at Tygerhoek Experimental Farm is given, describing each rotation system and crop sequence.

Chapter 4 will analyse the yield and quality data from the trials, focusing on wheat, barley and canola in particular. The driving factors for the trends seen in the yield and quality data are discussed. The differences in yield and quality between systems and sub-systems are examined as well as the yield changes over time. The different quality indicators for wheat and barley are also compared over time as well as between systems and sub-systems.

In Chapter 5 the gross margin and input cost data from the trials are analysed. This is also focused on wheat, barley and canola in particular. In the first part of Chapter 5, the gross margin data is discussed. The gross margins, allocatable variable costs and gross income for the different systems and sub-systems are compared. The same comparisons are done for the three crops over time. In the second part of Chapter 5, the input cost data from the trial is analysed. The input costs between systems and sub-systems are compared as well as those for the different crops over time. The three most prominent input costs are then examined individually over time, as well as between sub-systems over time. The reasons for the changes in gross margins and input costs will also be discussed and the most profitable sub-systems will be identified.

Chapter 6 provides the conclusions, summary and recommendations gleaned from this study.

Chapter 2 – Literature Review

2.1) Introduction

As stated previously, the increasing global population will put increasing pressure on land and water resources as food production will need to increase dramatically, making the quest for more sustainable food production methods even more critical for the future (FAO, 2018). The use of conventional agricultural practices such as the removal of crop residue and intensive tillage have degraded the soils at both a local (South African) and global level (Farooq *et al.*, 2011). This degradation, in turn, reduces the global capacity to produce food and is therefore unsustainable as the need for food is only increasing (Farooq *et al.*, 2011). Conservation Agriculture (CA) was put forward as a more sustainable method of food production and has been widely adopted worldwide (Kassam *et al.*, 2018). CA has been adopted to varying degrees throughout South Africa, with the Western Cape having one of the highest adoption rates (Swanepoel *et al.*, 2017).

CA relies on 3 principles, namely: (1) Minimal soil disturbance; (2) Permanent organic soil cover; and (3) Diversity through crop rotations (FAO, 2020). When combined, these 3 principles are aimed at rebuilding soil health which is negatively impacted by conventional agricultural practices. In 2008, the FAO introduced CA as an approach which aimed to be a resource-efficient crop production system based on all-inclusive combination of water, soil and biological assets and external inputs (FAO, 2008). CA is not a “one size fits all” method, every farm and farmer are unique, with a unique set of ecological and social characteristics. This is why the three CA principles are merely a guideline by which producers can build a foundation according to their unique farming environment. Although the original CA concept did not include a livestock component, the integration of livestock and pastures increased diversification, leading to further improvements in the system and increased profits and financial stability for the farmer (Basson, 2017).

The two main grain producing areas in the Western Cape are the Overberg and the Swartland. The majority of the farms in these areas are rain-fed and there has been a high adoption rate of conservation agriculture principles as it is seen as a more sustainable method of farming for the future (Hardy, 2004; Knott, 2015). There are a wide variety of crops which could be incorporated into crop rotation systems in the Western Cape, particularly in the Overberg, due to the higher proportion of summer rainfall in this region (Hardy, 2007). Crops commonly incorporated into a crop rotation system include wheat, oats, barley, canola and lupine among others.

The aim of this project was to evaluate how crop rotation systems should contribute to the long-term sustainability of farms in the Overberg and how the adoption of conservation agriculture will be beneficial for food security in the future. The goals for this project include identification of typical crop rotation systems for the area, assessing factors that contribute to sustainability and an evaluation of the systems and factors on farm level. Chapter 2 is an overview of the literature involving CA and will discuss CA in a global, national and regional context.

This chapter starts with an introduction to conservation agriculture, looking at the origins, concept and three principles of CA. The benefits and constraints of CA are then discussed, followed by an overview of the global spread of CA. A review of winter cereal production in South Africa, in the Western Cape in particular, is provided as well as a more in-depth look at the Overberg region, which is where the experimental trial discussed in this thesis is located. CA adoption in South Africa, the Western Cape and the Overberg region is discussed followed by an analysis of the crop systems in the Middle Rûens area of the Overberg, which is more specifically where the trial is located.

2.2) Introduction to Conservation Agriculture

A substantial increase in food production is needed to meet the demands of an ever-growing population. This requires the use of more sustainable food production systems that will be capable of providing food security whilst also withstanding pressures such as the growing population, climate change and shifting diets, while also reducing the environmental damage associated with conventional agriculture (Findlater *et al*., 2019). Conventional agricultural practices such as tillage and residue removal play a major role in the degradation of soil worldwide and have had a major impact on agriculture in many countries (Strauss, 2021). The degradation of productive agricultural soil has led to a decrease in the world's capacity to produce food, this in turn causes an increased risk of food insecurity, especially in South Africa and Sub-Saharan Africa where food security is a long-lasting issue (Swanepoel *et al.*, 2017). Should the agricultural community carry on as is, a point will be reached where food security can no longer be maintained (Strauss, 2021). To ensure adequate productive capacity in the future, methods which allow for the sustainable intensification of agriculture need to be more rapidly adopted.

Conservation agriculture (CA) was put forward as a method of sustainable production intensification for the future (Giller *et al.*, 2015) and has been widely promoted by organisations such as the Food and Agriculture Organization (FAO) of the United Nations, among others. CA is based on three main principles: (1) Continuous no- or minimal mechanical soil disturbance; (2) Permanent organic soil cover, usually in the form of crop residues or live mulch; and (3) Diversification of crop species grown in sequence or associations through rotations (Hobbs, 2007; Hobbs *et al.*, 2008; Kassam *et al.*, 2009; FAO, 2011; Friedrich *et al.*, 2012; Thierfelder *et al.*, 2015) . These three principles are interconnected, for example, a mulch which provides soil cover cannot be maintained when the soil is tilled. “True” CA is said to only be achieved when all three principles are implemented concurrently as this is what is needed for the system to reach its full potential (Strauss *et al.*, 2021). The benefits of adopting CA as a whole include: improved soil water infiltration – reducing erosion and improving water-use efficiency, a reduction in fertiliser and pesticide usage, enhanced nitrogen-use efficiency, and increased resiliency to economic shock and drought conditions (Findlater *et al.*, 2019; Strauss, 2021).

2.2.1) Origins of CA

The act of tillage has been synonymous with cultivation for millennia, reference to tillage can be dated as far back as 3000 BC in Mesopotamia, when humans were moving away from being hunter gatherers and adopting farming practices (Hobbs *et al.*, 2008). The development of agriculture over time has always included a tillage component. In the 19th century, the Industrial Revolution introduced mechanised machinery and tractors which became involved in tillage practices. In the modern day, there is a wide array of machinery available for tillage purposes. Tillage is known to provide many benefits to the farmer, but comes at a cost, both financially and environmentally, and will damage the natural resource base needed to produce food in the future. The continuous tillage of the soil has had an array of damaging effects, such as the reduction of soil organic matter and the loss of many soil microbes. This has also contributed greatly to the rising CO_2 levels in the atmosphere (Reicosky *et al.*, 2005).

CA has its origins in conservation-tillage which first came about as a response to the severe dust storms in the American Midwest in the 1930’s which were thought to have been caused by the intensive tillage practices in the area (Knott, 2015). Since then, there has been a move towards farming methods that involve less tillage, thereby reducing soil erosion (Hobbs *et al.*, 2008). Over time conservation-tillage practices evolved into a more holistic approach to farming, also including the use of crop rotations and crop residues or cover crops as permanent groundcover. This more holistic approach was then promoted under the label of conservation agriculture by the Food and Agriculture Organisation of the United Nations (FAO) as well as the European Conservation Agriculture Federation (ECAF) (Knowler & Bradshaw, 2007).

CA systems can be found on all continents (except for Antarctica) in all land-based agriculture, which supports the sentiment that CA principles can be locally adapted to be applicable in all agricultural landscapes and land uses. The implementation of true CA increases biodiversity and enhances natural biological processes both above and below ground (Hobbs *et al.*, 2008).

CA is a base for sustainable agricultural production intensification as it is often accompanied by other good agricultural practices such as integrated pest, water, weed and nutrient management as well as the use of quality seed (Kassam *et al.*, 2018). The methods in which the CA principles are applied can differ substantially as they can be adapted to suit specific biophysical conditions and farmer circumstances (Hobbs & Govaerts, 2010). CA is usually implemented in a series of changes to a farming system that improve sustainability and productivity.

The term "Conservation Agriculture" was adopted during the First World Congress on Conservation Agriculture in Madrid in 2001, which was held by the FAO and the European Conservation Agriculture Federation (Koohafkan *et al.*, 2001). CA systems are also known as Zero- or No- Till farming systems but only when no-tillage is combined with permanent soil cover, crop rotations and the direct planting of crop seeds (Kassam *et al.*, 2009). The concept of CA is a set of principles that aim to minimise and/or repair the damages caused by conventional agriculture. The goals of CA include the conservation, improvement and more efficient usage of natural resources through the integrated management of water, biological resources and soil combined with external inputs (FAO, 2008). This will contribute to the conservation of the natural environment and enhance sustained agricultural production (Hobbs *et al.*, 2008).

2.2.2) The Three Principles of CA

2.2.2.1) Permanent Organic Soil Cover

The maintenance of a permanent biomass soil mulch cover is implemented through the retention of stubble, root stocks, crop biomass, cover crops and other sources of *ex situ* biomass (Kassam *et al.*, 2018). This permanent organic soil cover should not be removed by ploughing the soil, over-grazing or the burning of crop residues. Optimal residue management should result in the improvement of overall soil health and quality (Reicosky, 2015), impacting favourably on yields and crop production.

The retention of surface residue plays a vital role in the protection of soil and soil organic matter against both wind and water erosion (Hobbs *et al.*, 2008). Residue should continuously be added to the soil to ensure that the soil retains the ability to withstand these stresses. The optimal scenario would be to have living plants and roots in the soil year-round, but this is dependent on climatic conditions (Smit, 2019). The burning of crop residues is commonplace amongst conventional producers, this however rapidly depletes soil nutrients and organic matter, whilst also contributing to air pollution. The burning of one kilogram of wheat residue will contribute an estimated 1.4 kilograms of CO_2 to the atmosphere (Magdoff & Harold, 2000).

Good crop residue management is especially beneficial to rain-fed CA systems. In rain-fed farming systems, rainfall is often unpredictable and seasonal dry periods are a regular occurrence. Water erosion happens when the energy of raindrops falling on bare soil causes the destruction of soil aggregates and the clogging of soil pores, resulting in decreased water infiltration, thereby increasing runoff and soil losses. Organic groundcover such as crop residues protects the soil surface and prevents damage to soil aggregates, thereby enhancing water infiltration and reducing erosion

(Hobbs *et al.*, 2008). Madari *et al.* (2005) found that the combination of no-tillage and residue cover resulted in higher aggregate stability and size as well as higher organic carbon in soil aggregates than those found under conventional tillage systems.

Crop residues also help moderate soil temperatures for optimal germination and root growth in hotter environments and insulate the soil surface which increases the resistance to heat and evaporation, leading to increased soil water availability which is vital in rain-fed systems (Adekalu *et al*., 2007; Cook *et al.*, 2006). No-tillage in combination with surface mulch have been found to reduce soil crusting and runoff, increase water infiltration, and give better yields than conventionally tilled soils (Thierfelder *et al*., 2005). This is very important in the tropics and subtropics but can be a hindrance in temperate climates and it can cause delays in soil warming during spring, causing delayed germination (Hobbs *et al.*, 2008). Surface mulch also promotes biodiversity and enhances nitrogen mineralisation in the soil (Thierfelder *et al*., 2005).

Climate change predictions show that rainfall patterns may become more erratic (Daniel, 2015), this is a threat to both soil and water resources worldwide, especially those used for agriculture. Without changes to current production practices, the forecasted climate changes can be expected to reduce yields. Conservation practices such as permanent organic soil cover can reduce the impacts of climate change (Panagopoulos *et al.*, 2014; Basche *et al.*, 2016).

Most soil related research is focused on understanding the physical and chemical processes within soil whilst the biological component of soil has been overlooked. The maintenance and/or improvement of soil productivity is becoming increasingly significant as the increasing food demand and climate change put more pressure on agricultural productivity (Lal *et al.*, 2011). With the introduction of CA principles, the restoration of soil biodiversity and biological activity has begun (Farooq & Siddique, 2015).

2.2.2.2) Continuous No or Minimal Soil Disturbance

Continuous no or minimal soil disturbance is achieved through the practice of broadcasting crop seeds, no-tillage seeding and the direct placement of plant material into untilled soils. Any harvest operation, cultural operation and/or farm traffic should also be kept to a minimum and cause as little disturbance as possible (Kassam *et al.*, 2018). Many of the advantages of minimal soil disturbance have been mentioned in the above section on permanent organic groundcover. In this section, comparisons will be made between no-tillage and tillage systems to highlight advantages of a no-tillage system which were not previously discussed.

Tillage is synonymous with soil disturbance and has long been thought to be an essential component of crop production. As concepts such as conservation tillage and zero tillage were introduced, the contrary has been proven true. There are a multitude of factors influencing whether tillage is the most appropriate option in a certain scenario, one of the main factors to be considered is soil type (Derpsch, 2001). Some reasons for which tillage may be used are (Hobbs, 2007):

- Integration of crop residues, soil amendments and/or weeds into the soil
- Controlling diseases and pests in the soil and residues
- Seedbed preparation
- Prevention of soil compaction

There are, however, many reasons not to use tillage in crop production systems. Farm machinery, such as tractors, which are needed for tillage, have high rates of fuel consumption which besides being costly also causes greenhouse gas emissions. Minimal or no-tillage will reduce both the cost of this and the associated emissions (Hobbs *et al.*, 2008). Tillage also causes more wear and tear on farm machinery, resulting in higher maintenance costs, whilst no-tillage increases the lifespan of farm machinery.

The practice of tillage is also very time consuming, whereas that time could be used elsewhere on the farm. No-tillage allows for timelier planting as tillage can cause delays in the planting of crops, which may cause reductions in yield potential (Hobbs & Gupta, 2003). The reduction in turnaround time in no-tillage systems allows for planting to be done on time, thereby increasing yields without increasing input costs.

Tillage causes decreases in soil organic matter (SOM) which is oxidized when exposed to air. This leads to the reduction of biological activity in the soil and causes soil degradation (Hobbs *et al*., 2008). In the short term, the mineralisation of SOM caused by tillage can liberate nitrogen which can improve yields but there is also soil carbon loss and the mineralisation of nutrients. No-tillage systems in combination with permanent soil cover can increase organic carbon in the surface layers of the soil (Lal, 2006). Producers often believe tillage can be used to reduce soil compaction. However, the practice of tillage itself can be a major source of compaction due to the heavy farm traffic associated with the practice. No-tillage reduces farm traffic, thereby reducing the number of passes over the land which decreases compaction (Hobbs *et al.*, 2008).

Soil is an integral part of life on earth, which is supported by the ecosystem services provided by the multitude of meso-, macro- and micro-fauna found in the soil (Hobbs *et al.*, 2008). CA focuses on the importance of soil health, preservation and sustainability whilst still using the soil as a medium for crop production.

2.2.2.3) Diversity through Crop Rotation

The diversification of crop species can be achieved by implementing a cropping system which has crops in rotations, and/or associations and/or sequences. These can involve both perennial and annual crops and include a mix of leguminous and non-leguminous crops (Kassam *et al*., 2018).

Some limiting factors to production include weeds, pests and diseases which often require high levels of external inputs. These risks are very common in conventional and mono-cropping agricultural systems. Crop rotation has been used as an agricultural management tool since ancient times (Hobbs *et al.*, 2008). Crop rotations can assist in breaking pest and disease cycles, thereby increasing yields and contributing significantly to the success of CA production cycles (Tarkalson *et al*., 2006). Crop rotations promote the replenishment of soil fertility whilst also minimising pest and disease build-up (Trenbath, 1993). There is no single best crop rotation sequence - rotation systems are site-specific and could be cash crop-only rotations or crop-pasture rotations - it is dependent on what will work on the specific farm at hand.

By using strategic adaptions of crop rotation sequences in combination with other aspects of CA, there can be greater success of crop production in more marginal areas. Crop rotations can also contribute to the increased profitability of a cropping system as the combination of the reduced labour and input costs, timeliness of planting and higher yields associated with well-planned rotations can increase overall profits (Hardy *et al.*, 2011; Crookes & Strauss, 2017) . This contributes to the overall sustainability of the system.

Crop rotations using different crops with different rooting systems, in combination with no-tillage, facilitates a better root channel network and increased macro pores in the soil (Hobbs *et al.*, 2008). This improves water infiltration into the soil and increases overall soil quality. Crop rotations also increase microbial diversity in the soil, which reduces the risk of disease and pest outbreak.

The use of legumes in a crop rotation system has the advantage of increasing soil nitrogen levels as legumes are known for biological nitrogen fixation (Giller *et al.*, 2009). Some farmers believe that using mineral fertiliser is the fastest and best way of righting any decline in soil fertility however, this alone will not be a long-term solution to the problem. The use of mineral fertiliser in combination with CA cropping systems allow for a build-up of organic carbon which contributes to the long-term sustainability of the system (Thierfelder *et al*., 2012).

There are both benefits and challenges associated with the adoption of CA. These will be discussed below.

2.3) Benefits of CA

2.3.1) Improved Soil Water Retention and Reduced Erosion

CA aims to make crop production more sustainable in the long-term and one aspect of this is efficient water usage. In dryland farming systems it is crucial to conserve water and CA can maintain and improve soil porosity and increase soil organic matter content thereby extending the availability of soil water for the crops in times of drought, while improving the soils general rooting environment (Kassam *et al.*, 2009).

The rainwater retention of the soil is usually determined by the level of water evaporation, the rate of water infiltration and the water holding capacity of the soil (Jat *et al*., 2012). CA has been found to significantly improve soil stability and cohesion while reducing the surface compaction of the soil, allowing for higher rates of soil water infiltration (Knott, 2015). The higher water infiltration rates combined with permanent soil cover and no-tillage reduces surface water runoff which in turn greatly reduces erosion in agricultural landscapes (Thierfelder & Wall, 2009).

One of the three main principles of CA is permanent soil cover by either organic matter, crop residues or a mulch (Thierfelder & Wall, 2009). This soil cover reduces evaporation of water from the soil surface by protecting the soil from direct sunlight and raindrop impact and by increasing the resistance to air flow across the soil surface (Jat *et al.*, 2014). Rainwater is captured by the surface cover (crop residues, mulch etc.) and is gradually released into the soil which also prolongs water availability for crops. It has been found that surface cover that increases the soil organic matter by one percent can increase the water holding capacity of the soil by up to three percent (Jat *et al.*, 2014). The water conservation aspect of CA can therefore make a significant difference in dryland farming systems.

2.3.2) Improved Soil Quality

Conventional tillage practices are known to degrade soil over a long period of time, reducing its productivity potential and costing the producer more as increased levels of external inputs are needed to maintain profitable yields. Tillage also destabilises the soil aggregates, resulting in loose topsoil which is more exposed to erosion by wind and/or rain (Kooper, 2020). CA uses a zero- or no-tillage approach and limits any farm traffic on the soil, this lessens soil compaction and degradation and reduces the loss of soil organic matter (Thierfelder & Wall, 2009).

Soil fertility traditionally refers to the concentration and quantity of available soil nutrients in the soil. The more modern concept of soil fertility focuses on the nutrient levels which are accessible to plant roots and includes the interactions between the plants, the soil and the water system therein (Knott, 2015). A core principle of CA is the maintenance of permanent organic soil cover, either through crop rotations, cover crops or a living mulch. This adds to soil organic matter and stabilises soil aggregates as the plant matter is left to naturally decompose, without any tillage disturbances (Raiesi & Riahi, 2014). This in turn enhances the soil biology and creates a fertile, biodiverse zone in the soil. Above and below ground biodiversity are enhanced in soils with minimised disturbance and organic groundcover (Hobbs, 2007). The soil becomes a good habitat for beneficial insects, earthworms and other beneficial soil mesofauna which improve soil fertility and productivity.

Organic matter is known to release nutrients into the soil via a slow-release mechanism which provides stable quantities of plant-available nutrients over months and years (Knott, 2015). Organic soil covers such as mulches protect the soil from direct sunlight and provides an insulating barrier which also moderates the soil temperature (Hobbs, 2007). This contributes to the sustainability and resiliency of CA systems.

2.3.3) Increased Nutrient Use Efficiency

Permanent organic soil cover combined with minimal tillage and crop rotations result in a higher level of biodiversity in the soil, leading to higher nutrient levels than what would be found in conventionally tilled soils (Hobbs, 2007). The use of deep-rooted cover crops in a crop rotation cycle with cash crops allows for nutrients from deeper within the soil to be used by the subsequent cash crops (Kooper, 2020). Soil organic matter retention is also increased under CA systems through the integration of nitrogen rich legume crops into crop rotation cycles (Knott, 2015). This also reduces nitrogen leaching and lessens the need for chemical fertilisers as increased levels of microorganisms retain the nitrogen in the residue (Friedrich *et al*., 2014; Knott, 2015).

In the initial stages of CA implementation, microorganisms hold most of the mineral nutrients, but as microbial activity increases over time, the nutrients become more readily available and carbon is accumulated in the soil (Kassam *et al.*, 2009). Higher levels of organic nitrogen have been found in soil under CA than in conventionally tilled soils. After years under CA management, the health and structure of the soil stabilises and the increased microbial activity allows for the natural recycling of carbon, nutrients and water (Knott, 2015), thereby improving overall soil health and productivity and decreasing the need for synthetic inputs.

2.3.4) Increased Yields and Crop Productivity

During the initial stages of CA implementation, crop yields could remain the same, increase or even decrease as this depends on the climatic conditions of the area and the initial state of the soil (Jat *et al.*, 2012). Over time, CA improves soil health and fertility through the reduction of erosion and surface crusting, increased infiltration and soil water content and improved soil structure as soil aggregates are more stable and evenly distributed (Hobbs *et al*., 2008; Farooq *et al.*, 2011). The physical, biological and chemical improvements in the soil and the added environmental recovery are linked to higher and more stable yields over time (Knott, 2015; Kooper, 2020). Crop rotations using nitrogen fixing legumes with subsequent nitrogen absorbing crops such as wheat also improve crop yields (Jat *et al.*, 2014). Rotations also assist with pest, disease and weed control which can also beneficially impact crop yields (Strauss, 2021).

In dry Mediterranean climates in different parts of the world, CA has been shown to improve yields by up to 100% compared to those of conventional tillage systems (Kassam *et al.*, 2012). CA also leads to better drought tolerance as the improved soil structure allows for better water infiltration and increases the water holding capacity of the soil (Jat *et al.*, 2014). This minimises the impact of dry periods on rain fed crops.

CA also has the potential to improve productivity levels, increasing profits and making it possible to cultivate larger areas of land using no-tillage cultivation when compared to conventional tillage methods (Jat *et al*., 2012). CA also allows for planting to be done closer to ideal planting time as it removes the need to wait for favourable weather conditions to plough the land before planting (Hobbs, 2007; Knott, 2015). The impact that CA will have on crop yields and other factors affecting productivity will differ regionally as the CA practices used and the results of those practices are highly site specific (Farooq *et al.*, 2011).

2.3.5) Reduced Input Costs

The reduced soil disturbance in CA means that the use of machinery such as tractors is drastically reduced. This reduces input costs such as fuel, maintenance and repairs for farm machinery (Knott, 2015). The reduced dependence on tractors and other farm machinery limits CO_2 emissions and limits the reliance on fossil fuels (Kooper, 2020). Strategic use of crop rotations and organic ground cover can lower labour costs and assist in weed, pest and disease control, reducing the levels of agrochemicals needed to keep the soil healthy. The use of cover crops and increased soil organic matter retention reduces nitrogen leaching and slowly releases nutrients into the soil, reducing the need for chemical fertiliser (Jat *et al.*, 2012; Kassam *et al.*, 2012). The integration of legumes into crop rotation cycles fixes nitrogen in the soil, making it available for subsequent cash crops and reducing the need for chemical nitrogen.

Crop rotations also assist with weed management as different herbicides can be used for controlling weeds during different rotations, lessening the reliance on specific herbicides in the long-term (Knott, 2015). Crop rotations can also disrupt pest life cycles and disease build-up, reducing the need for chemical pesticides (Kassam *et al.*, 2012). The use of crop rotations, organic ground cover and minimal soil disturbance all act to lower input costs in some way. The lowered input costs in combination with the potentially higher yield and environmental benefits will increase overall profitability under CA.

2.3.6) Reduces Environmental Degradation and Increases Biodiversity

Conventional agriculture is responsible for a large amount of environmental degradation, from soil erosion to the breakdown of ecosystems and the loss of biodiversity. The micro-, macro- and mesofauna found in the top zone of soil are responsible for almost all the ecosystem services and environmental functions supporting life on earth (Strauss, 2021). This highlights the importance of restoring and preserving soils, which is an integral component of CA.

All three principles of CA are aimed at reducing the impact of agriculture on the environment and making the best use of environmental functioning and ecosystem services. The no-tillage aspect of CA minimizes the disturbance of microorganisms and other soil biota (Jat *et al.*, 2014). Permanent organic ground cover through the retention of crop residues creates an ideal environment for all soil biota which greatly improves soil fertility and structure. This also reduces the need for synthetic inputs which are potentially harmful to the environment. Cover crops recycle nutrients, provide food for soil organisms and regulate the soil surface temperature which benefits the biota below the surface (Kooper, 2020). Above-ground biodiversity also benefits from cover crops as they provide food for mammals, reptiles, birds, and insects (Jat *et al.*, 2014).

The disturbance of the soil surface hastens the mineralisation of organic matter, which involves the conversion of plant residues into CO_2. Tillage involves intense soil disturbance resulting in increased organic matter mineralisation and increased CO_2 emissions into the atmosphere (Knott, 2015). By removing the tillage component as well as reducing farm traffic and reliance on fossil fuels, CA greatly reduces the CO_2 emissions associated with agricultural production. The CA system is both environmentally and financially beneficial primarily because it reduces the environmental impact of agriculture as well as the need for synthetic inputs and increased ecosystem services. In combination these factors result in decreased costs for the producer (Strauss *et al.*, 2021).

Some of the constraints of adopting CA are discussed in the next section.

2.4) Constraints of CA

2.4.1) Mental Change Needed for Producers

For farmers to change from a conventional tillage system to a successful CA system they will require a shift in mindset. Tillage is an age-old practice which has always been associated with the cultivation of crops and changing farmer's mindsets towards this will require evidence, time and commitment (Kooper, 2020). For a producer to change his/her perception of and adopt a foreign concept will also require them to renounce current assets such as machinery, skills and knowledge (Knott, 2015).

Many older farmers are more hesitant when it comes to change and risk-taking, but younger farmers are more willing to adopt new, modernised techniques and take bigger risks (Jat *et al*., 2012). Support in the form of government subsidies and research groups will assist in mitigating the risks associated with adopting CA and may encourage more farmers to consider this. Changing the mindsets of farmers is one of the largest barriers to widespread CA adoption (Hobbs & Govaerts, 2010).

2.4.2) New Skills and Machinery Needed

CA is a knowledge intensive process and requires both time and commitment from the farmer. CA requires a different management approach to that of conventional agriculture and it also requires different machinery and new skills for operating the machinery (Jat *et al*., 2012). To successfully adopt CA, it is crucial to purchase new, specialised machinery. This is often a major barrier to smaller scale farmers and many farmers in developing countries where it may be difficult and costly to acquire the necessary machinery (Hobbs *et al*., 2008). Crop residues, for example, pose a challenge for the planting and seeding of crops by farmers. It may be necessary to purchase new tractors and new implements in order to plant as some implements are not suited to older tractor models (Jat *et al*., 2012). This makes the development and availability of new, specialised machinery essential. The machinery will need to be efficiently used for the seeding of untilled, residue covered soils to a suitable depth for germination and nutrient use efficiency (Hobbs, 2007). Farmers will need proper training and guidance on how to effectively use the machinery to the best of its ability which will require time and commitment. Maintenance of machinery will also be needed to prevent issues and increase the longevity of the equipment. A lack of knowledge and skills in this regard may result in incorrect soil fertility management and input usage which may in turn negatively affect yields (Jat *et al*., 2012).

2.4.3) Retention of Crop Residues

Crop residue retention is an integral part of CA and is directly attributed to many of the benefits associated with CA. However, the retention of crop residues is an issue under many farming conditions, and this is a big constraint to CA adoption in many areas. Cereal and legume residues are highly valued as livestock fodder which often takes preference over residue retention for the soil cover aspect of CA. In many developing, sub-tropical countries fodder is in short supply as farm sizes are typically smaller and there is often a lack of communal grazing land (Jat *et al*., 2012). In many rural communities, livestock have great economic and cultural value (Basson, 2017). Livestock can be used for milk, meat, manure, and as draught animals. Livestock are often used as investments and/or risk insurance and are also a cultural sign of wealth and prosperity (Jat *et al.*, 2014). Therefore, crop residues are generally used as fodder rather than as a mulch as there is a high demand for fodder in areas with high levels of livestock production, especially in developing countries.

Due to a growing middle class, the demand for animal products is projected to increase, which will result in an increase in both animal populations and fodder demands (Kooper, 2020). This requires new strategies, allowing producers to increase biomass production to ensure there is a sufficient amount of residue for both fodder and residue retention purposes. Selected crop rotations can be used as a way of increasing biomass production (Jat *et al*., 2012). In the tropics and sub-tropics, biomass production is already limited, and the issue of communal grazing is very prevalent. Many small-scale farmers are unable to plant cover crops in the fallow season due to economic issues and keeping livestock off their land during this time will require fencing which is also an added cost (Jat *et al.*, 2014). This may also create tensions in the local community and challenge the traditional rights of other community members who consider the crop residues a public good during the fallow season. Macrofauna such as termites are also an issue as they cause damage to and reduce biomass in many parts of the world.

2.4.4) Transition Phase When Converting to CA

Producers transitioning from a conventional agricultural system to a CA system often need a high initial capital investment. The new equipment needed to work in no-tillage soils is costly and during the initial stages of CA adoption, inputs such as labour, fertilisers and pesticides may need to be increased to achieve the same yields as if under conventional agricultural systems (Kooper, 2020). For the first few years, the difference in productivity and yields between a conventional and CA system may be insignificant or even lower in the CA system. The producer will usually only start seeing significant differences and benefits after several years and some producers are unable to take this economic risk. Figure 2.1 below shows the transitional phases of adopting CA (FAO, 2001; Knott, 2015):

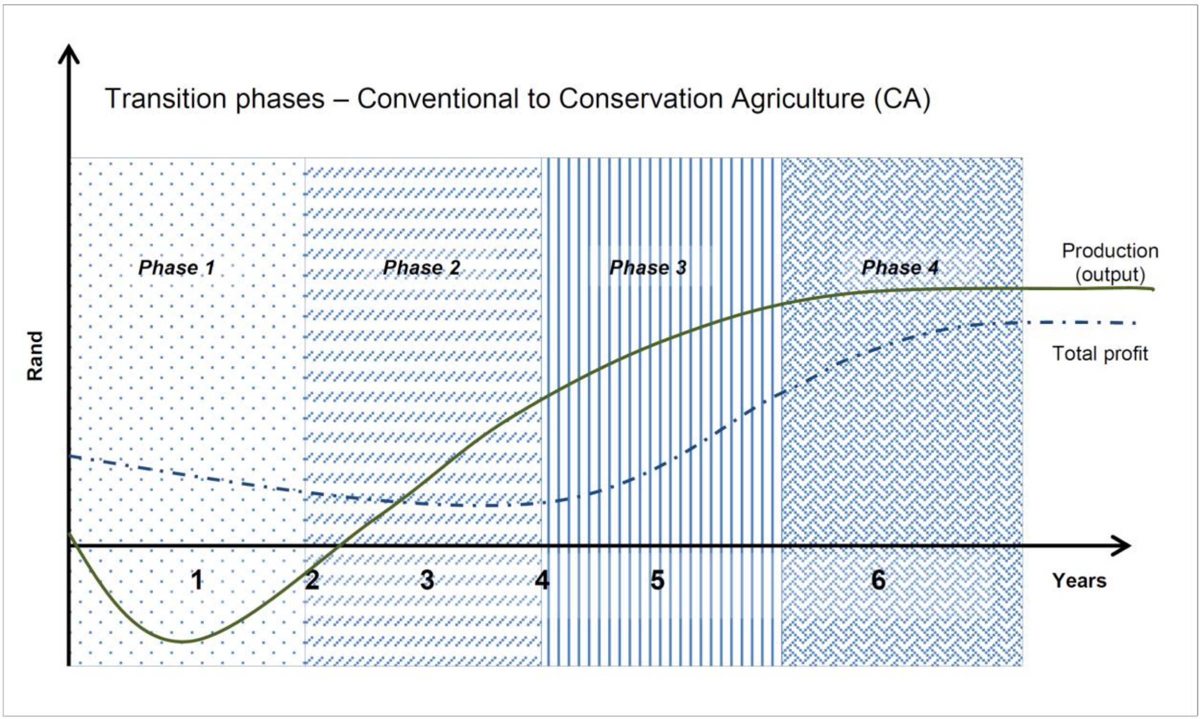


Figure 2.1 - The transitional phases from conventional agriculture to conservation agriculture (Source: FAO, 2001; Knott 2015).

Farmers often only adopt one or two principles of CA to start with so as to mitigate the risk associated with transitioning to a full CA system (Jat *et al*., 2012). However, all three principles of CA need to be applied concurrently in order to reap the full benefits of the CA system as a whole and only applying one or two principles may even be detrimental. No-tillage has been found to reduce yields when adopted alone, as tillage helps to control weeds, pests and diseases and additional inputs and selected crop rotation systems are needed in the place of tillage (Findlater *et al.*, 2019).

Soil type also plays an important role in the adoption of CA. The original soil condition and type can impact the effect that CA will have on the soil, especially with regards to the no-tillage aspect of CA. During the initial adoption stages of CA, no-tillage may be a problem if, for example, lime is required in acidic soils as it cannot be incorporated into the soil through no-tillage. Over time, increased infiltration rates will allow unincorporated lime to move into deeper soil layers (Derpsch, 2001). Fresh biomass retention of crops such as cereals, with a high carbon: nitrogen ratio, as a mulch during the early stages of CA adoption, can cause the net immobilisation of nutrients in the soil, especially nitrogen. This may lead to nutrient deficiencies and would require nutrients to be applied externally, which may be costly (Jat *et al.*, 2014). This should improve over time as soil health and water infiltration improve.

There is the possibility of yield reductions during the conversion phase between conventional agriculture and CA. This is mainly due to higher weed prevalence caused by no-tillage, lower germination rates, higher levels of pests and diseases, soil nutrient immobilisation, potential water logging in soils with poor drainage and a skills deficit with regards to the new methods and equipment (Jat *et al.*, 2012). This is a major constraint to small scale farmers as many are reluctant to taking risks and do not have the economic resources to fall back on should there be a lack of productivity when trying a new system (Jat *et al.*, 2012).

2.4.5) Need Assistance and Support for Farmers/ Lack of Research

The adoption of CA can be daunting to producers, as it is a very knowledge-intensive practice. It is also a big financial investment and producers need continuous support in terms of training, knowledge and a supply of necessary inputs, such as herbicides, during the transition phase (Knott, 2015). Acquiring and implementing the new equipment, methods and technology also requires assistance and often funding or financial support. Farmer support groups, machinery pools and proficient extension services will aid the uptake of CA in rural communities.

It can be difficult for small holder farmers to adopt CA without policy and institutional support. The lack of government subsidies and crop insurance makes these producers more vulnerable to climate and weather risks and makes the transition to CA even more precarious (Findlater *et al*., 2019). Another issue is the lack of sufficient research on cropping systems, cover crops, specialised machinery and weed control for CA (Jat *et al.*, 2014). There is also very limited research on the long-term effects of CA on soil quality and crop yields under different climatic conditions (Jat *et al.*, 2012). This lack of research unnerves farmers who are already hesitant to adopt CA. Evidence of CA's successes, especially long-term, will be helpful in illustrating the benefits of the CA system to conventional producers.

2.4.6) Infestation of Weeds, Insects and Pathogens

A major challenge to the successful adoption of CA is weed management. The lack of tillage under CA systems can lead to major weed infestations. The use of herbicide alone is not enough to control weed populations, especially when crop residues cover the soil surface (Jat *et al.*, 2014). In the early stages of CA adoption, higher levels of herbicides and crop rotation systems are needed to control weed populations. This is an issue in many developing countries as herbicides are not always readily available and are costly. This problem may also require site-specific knowledge as the producer needs to be informed on the most recent and effective herbicides as well as the application technology to control the weeds on their specific area of land (Basson, 2017). During the early stages of CA adoption, there will be an increase in labour costs to control the weeds, but over time this is expected to decrease due to continuous early weeding (Jat *et al*., 2012).

The use of crop residues as mulch in CA systems can create a favourable environment for harmful insect-pests, diseases, rodents and nematodes (Jat *et al*., 2012). This is due to the moisture retention, temperature regulation and food supply present because of the crop residues. This may require an increase in pesticide usage, but this is site-specific as different areas struggle with different pests and diseases. All of these factors are constraints to the adoption of CA, especially by small holder farmers in developing countries where access to the necessary pesticides and herbicides may be limited.

2.5) The Global Spread of Conservation Agriculture

Transformation of agricultural production systems is progressing globally and is mostly farmer-led. CA is a proposed method for the sustainable intensification of crop production which has grown in popularity over the years and the adoption of CA globally is increasing year by year.

In 2008/9 the global extent of CA cropland was estimated to be 106 M ha, which was 7.5% of all global cropland (Figure 2.2). In 2013/14 it had increased to cover about 157 M ha (11% of global cropland), indicating an increase of approximately 51 M ha over a 5-year period. In 2015/16 the extent of CA cropland was an estimated 180 M ha (12.5% of global cropland), which was an increase of 74 M ha (69%) over the 7-year period since 2008/9 or about 23 M ha (15%) over the 2-year period since 2013/14 (Kassam *et al.*, 2018). The most recent figures, those which will be used in this section, are from 2015/16 and were published by Kassam *et al.* in 2018.

Between 1999 and 2013, the area of CA cropland expanded at an estimated rate of 8.3 M ha per year (from 72 to 157 M ha). Since 2008/9 the rate of expansion has increased to an estimated 10.5 M ha per year (from 106 to 180 M ha). This shows how the interest in CA as a means of more sustainable agricultural intensification is steadily increasing. The initial expansion of CA was mainly in North and South America as well as New Zealand and Australia. More recently it is also happening in Asia, Europe and parts of Africa. Since 2008/9, the number of countries in which CA has been adopted has increased from 36 to about 55 in 2013/14 and to 78 in 2015/16 (Kassam *et al*., 2018).

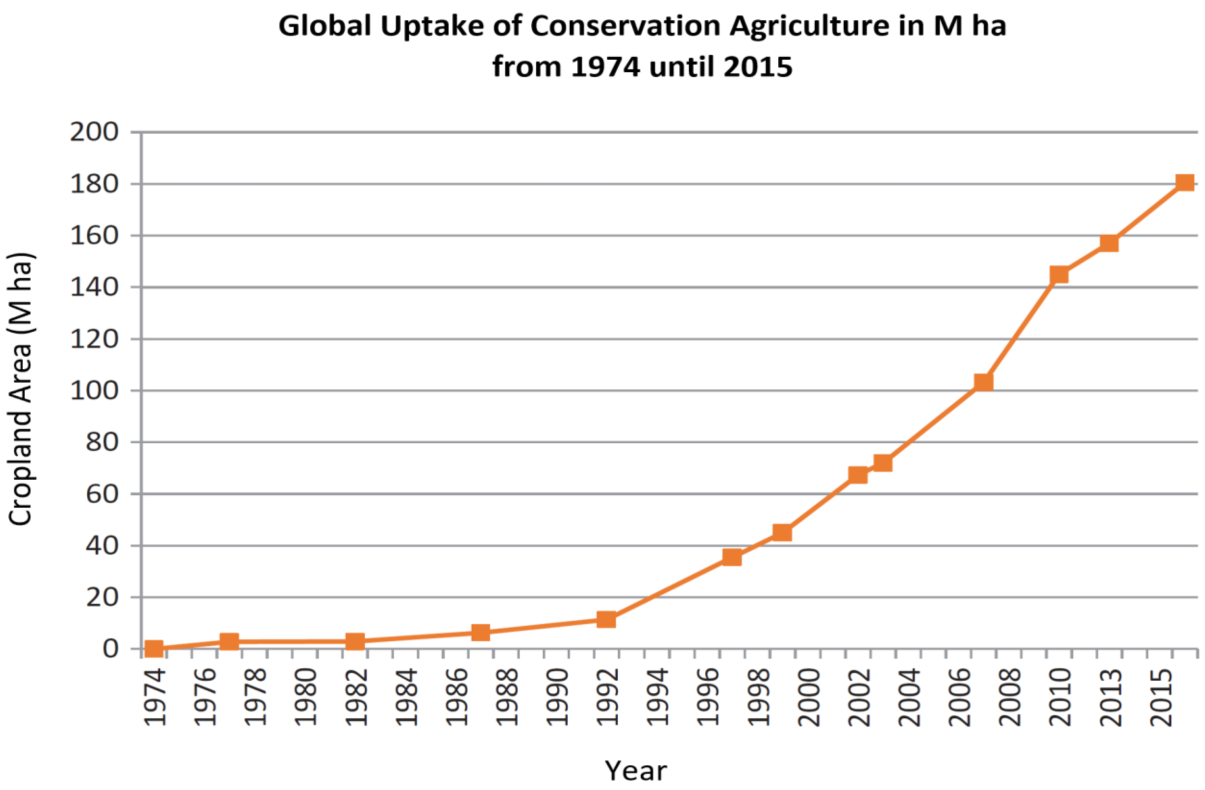


Figure 2.2 - The global adoption of conservation agriculture from 1974 until 2015 (Source: Kassam *et al*., 2018)

The global leaders of CA adoption are North and South America with approximately 69.9 M ha and 63.2 M ha of cropland under CA, respectively (Table 2.1). This is followed by Australia and New Zealand which combined have an estimated 22.7 M ha of cropland under CA. The regions with the lowest rates of CA adoption globally are Europe, with an estimated 3.6 M ha under CA, and Africa with approximately 1.5 M ha of cropland under CA (Kassam *et al*., 2018).

Table 2.1 - Area of cropland (M ha) under CA by region in 2015/16, area as a percentage of the global CA cropland and area as a percentage of cropland in each region (Source: Kassam *et al.,* 2018).

Region	CA Cropland Area (M ha)	Percent of Global CA Cropland Area (%)	Percent of Cropland Area in the Region (%)
South America	69.90	38.7	63.2
North America	63.18	35.0	28.1
Australia & NZ	22.67	12.6	45.5
Asia	13.93	7.7	4.1
Russia & Ukraine	5.70	3.2	3.6
Europe	3.56	2.0	5.0
Africa	1.51	0.8	1.1
Global Total	**180.44**	**100**	**12.5**

2.6) Overview of Winter Cereal Production

2.6.1) Agriculture in South Africa

South Africa is a semi-arid country (30th driest country in the world), making water one of the most valuable natural resources, especially for the agricultural sector in South Africa (Kuschke & Cassim, 2019). Water is a key constraint to agricultural development and plays a major role in the profitability and functionality of the industry. Agriculture contributes an estimated 2.5% to the total Gross Domestic Product (GDP) of South Africa and is also a key sector with regards to providing employment and earning foreign exchange. In 2019, an estimated 885 000 people were employed by the agricultural sector (Galal, 2021). If the entire agricultural value chain is considered, the sector is estimated to contribute about 12% to the national GDP (Kuschke & Cassim, 2019). In 2020, the agricultural sector added an estimated R 78 billion to the national GDP (Figure 2.3). The agricultural sector is interconnected with the rest of the economy and a large portion of the agricultural output is used for intermediary production in other sectors.

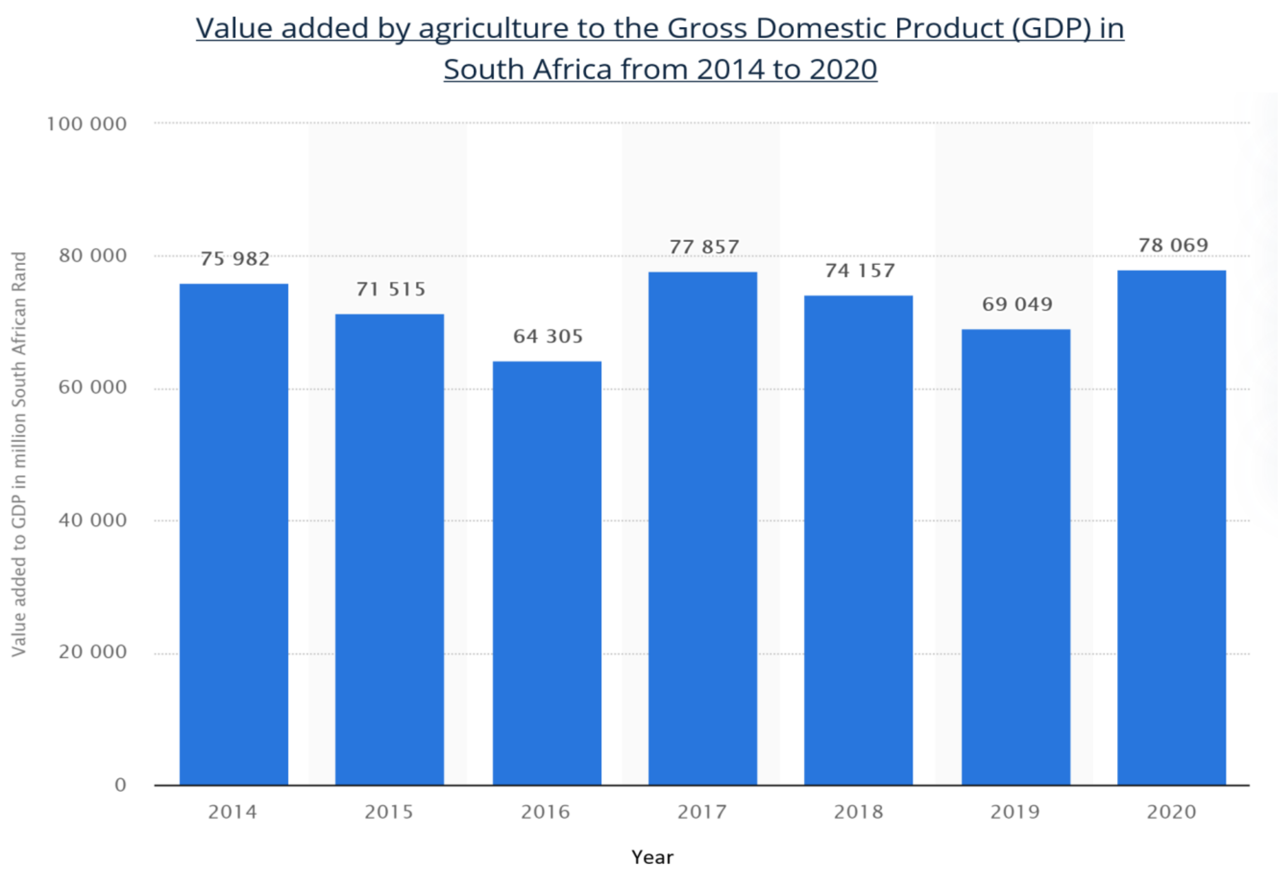


Figure 2.3 - The value added by the agricultural sector to the annual GDP in South Africa from 2014 to 2020 (Source: Galal, 2021).

In 2018, the total land use for commercial agriculture in SA was 46.4 million hectares (37.9% of total land area of SA). Of this, 36.5 million hectares is used predominantly for grazing and 7.6 million hectares are considered to be arable land and is used mainly for field crop production (StatsSA, 2020).

2.6.2) Agriculture in the Western Cape

The Western Cape Province is the 4th largest province in South Africa, with a land area of approximately 12.9 million hectares. Of this land area an estimated 11.5 million hectares are farmland but only approximately 2.4 million hectares (19% of total land area) are considered arable (Van Zyl *et al.*, 2014). Approximately 1.8 million hectares are under field crop production (WCDA, 2020). The Mediterranean climate in the Western Cape is unique to the rest of South Africa, with cool, wet winters and hot, dry summers. This makes the agricultural industry in the Western Cape unique to those in the rest of SA as the Western Cape has a very diverse landscape with a multitude of climatic conditions, allowing the production of a wide variety of agricultural products. The production of high-quality produce, such as fruit, table grapes and wine, has made the Western Cape the dominant province in terms of agricultural exports in SA (Kuschke & Cassim, 2019). The Western Cape agricultural sector is known for its production stability and is supported by well-developed infrastructure for input supply and output processing (Van Zyl *et al*., 2014). In 2019, the Western Cape agricultural sector contributed 17.8% to the national agricultural GDP (Partridge *et al.*, 2020). The agricultural sector in the Western Cape also generates foreign reserve, income and employment for the local economy. The Western Cape agricultural sector contributes approximately 4% to the provincial economy. However, when upstream and downstream linkages are included, this estimate rises to an approximate 9.4% contribution to the provincial economy (Kuschke & Cassim, 2019). The agricultural and agro-processing industries are responsible for 18% of formal employment in the Western Cape (Kuschke & Cassim, 2019).

Winter cereal crops have been grown in the Western Cape since the 1600's, the main crop being wheat but also including oats, barley, canola and some other small grain and legume crops (Hardy, 2007). Wheat and barley are mainly grown as grain crops whilst other cereals are grown mostly as a pasture crop, with some grain being grown for niche markets (Jordaan, 2002). The Western Cape is the main wheat producing province in South Africa and produced approximately 45.2 % (634 000 tons) of the country's wheat in 2019 (Figure 2.4). These winter cereal crops are usually grown in the winter and all-year rainfall regions of SA (Hardy *et al.*, 2011).

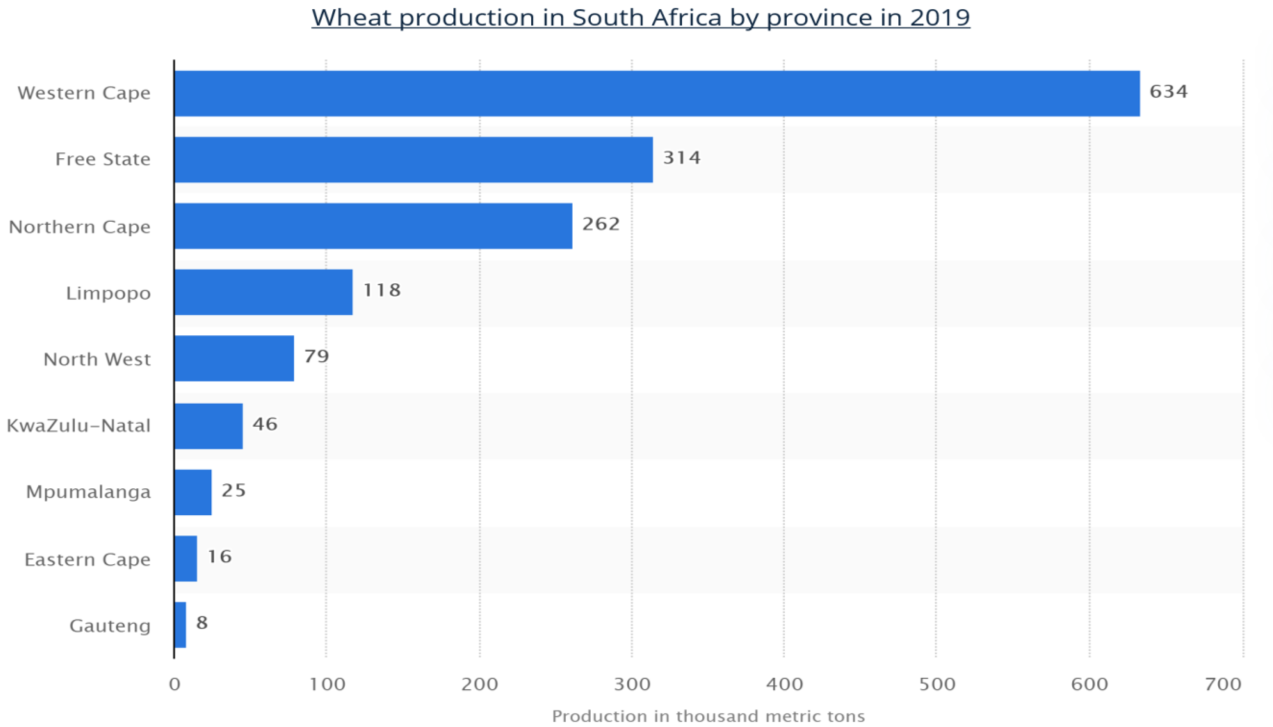


Figure 2.4 - The amount of wheat produced per province in South Africa in 2019 (Source: Galal, 2021).

Previously wheat, barley and oats were the predominant crops grown in the winter and all-year rainfall areas but as crop rotations became a more popular practice amongst farmers, crops such as canola, lupines, medics and lucerne were also incorporated into cropping systems.

2.6.3) Wheat production

Wheat is the second most important cereal crop grown in South Africa, following maize. The total area planted to wheat in 2018 was 503 000 hectares, with a total wheat production of approximately 1.8 million tons (DAFF, 2019). Most of the wheat produced in SA is for human consumption with a smaller quantity being used in the animal feed industry.

There have been significant changes in the South African wheat industry since the mid-1900's. In 1985, the total area planted to wheat in SA was 1 983 000 hectares, with a total production of 1 691 000 tons and a gross value of R 534 916 000. In 2019, the area planted to wheat decreased to 540 000 hectares, with a total production of 1 508 000 tons and a gross value of R 6 115 034 000, as illustrated in Figures 2.5 and Figure 2.6 (DAFF, 2020). Although the area planted to wheat declined drastically, there was an increase in efficiency, productivity and quality due to scientific improvements in the field as well as improvements in technology (Smit *et al.*, 2010). There was also an increase in yield per hectare. In 1983 approximately 1 ton/ha was produced on average, while the average yield was 3.6 ton/ha in 2018 (Smit *et al*., 2010; DAFF, 2019). The domestic demand for wheat in SA is approximately 2.8 million tons annually. The local wheat production in SA, however, has consistently failed to meet that requirement, causing SA to be a net importer of wheat (Smit *et al*., 2010).

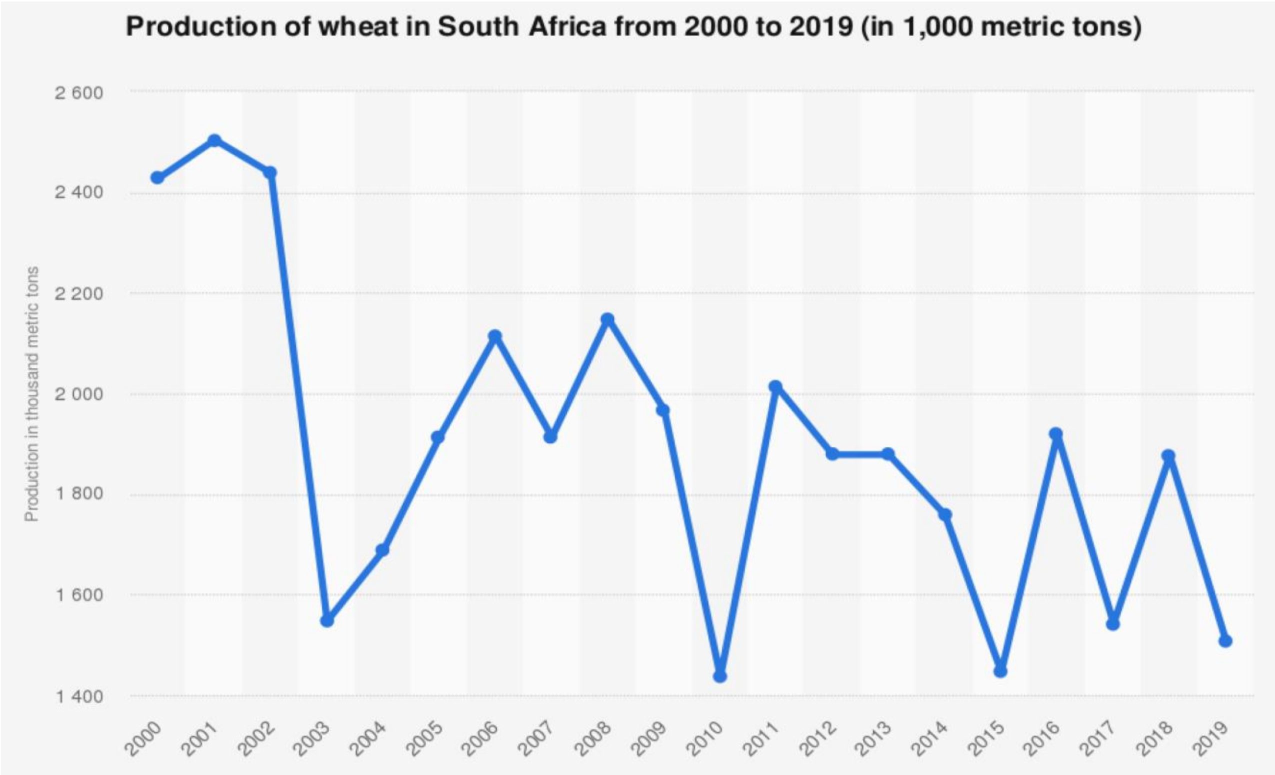


Figure 2.5 - The production of wheat in South Africa from 2002 until 2019, measured in 1000 metric tons (Source: Galal, 2021).

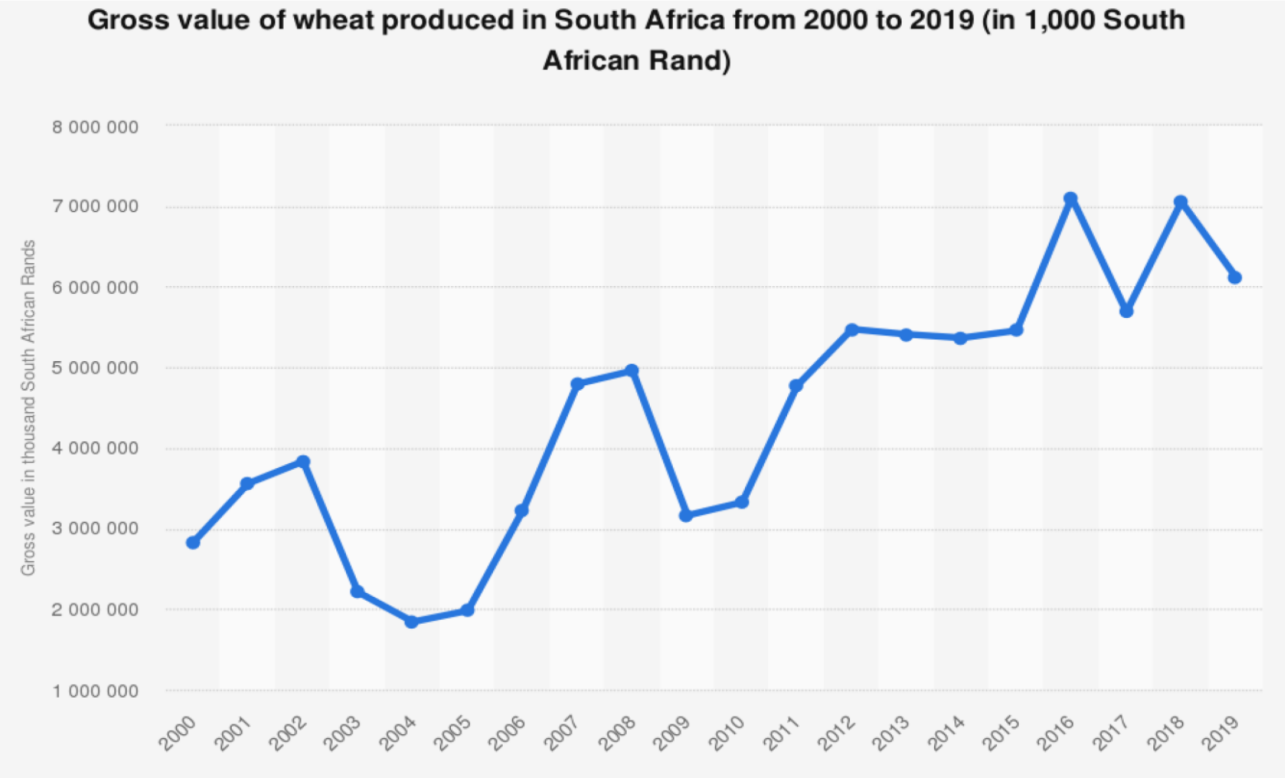


Figure 2.6 - The gross value of wheat produced in South Africa from 2000 until 2019, measured in 1000 South African Rand (Source: Galal, 2021).

The decline in the area planted to wheat can be attributed to a multitude of factors, one of which is the structural changes in the wheat industry in SA. Before 1997, there was a single marketing channel for the wheat industry, which was controlled by a centralised organisation known as the Wheat Board (Smit *et al*., 2010). The Wheat Board controlled imports and exports and fixed wheat prices. Local millers were encouraged to buy from local wheat producers, providing a more stable income to farmers. The Wheat Board's exclusive purpose was the protection of the local supply chain through the manipulation of the prices of imports and exports (Van Der Merwe *et al.*, 2016).

In 1996 the Wheat Board was decommissioned, and this led to the deregulation and liberalisation of the South African wheat market. The local wheat market was now exposed to the international wheat market and international competitors were able to take a more prominent position in the local wheat industry's domestic supply chain. The deregulation and liberalisation of the South African wheat industry opened up opportunities for the local industry, but also exposed it to increasing risks in the form of volatile supply and demand conditions and fluctuating prices (Van Der Merwe *et al*., 2016).

2.6.4) Barley Production

Barley is the second most important small grain in SA, after wheat. Barley is a winter cereal crop and this restricts its production areas in SA to specific areas in the Overberg, Northern Cape and some areas in North West province (DAFF, 2017). In 2019, the Western Cape was responsible for 80% of South Africa's barley production and is a large contributor to the expansion of the barely industry in SA (DAFF, 2020). The Overberg area is the main barley producing region in the province. The area planted to barley in SA is relatively small and in 2019, an estimated 132 000 hectares were planted, which resulted in a production of approximately 345 000 tons of barley, with the gross value of production being approximately R 1.05 billion, as illustrated in Figures 2.7 and Figure 2.8 (DAFF, 2020).

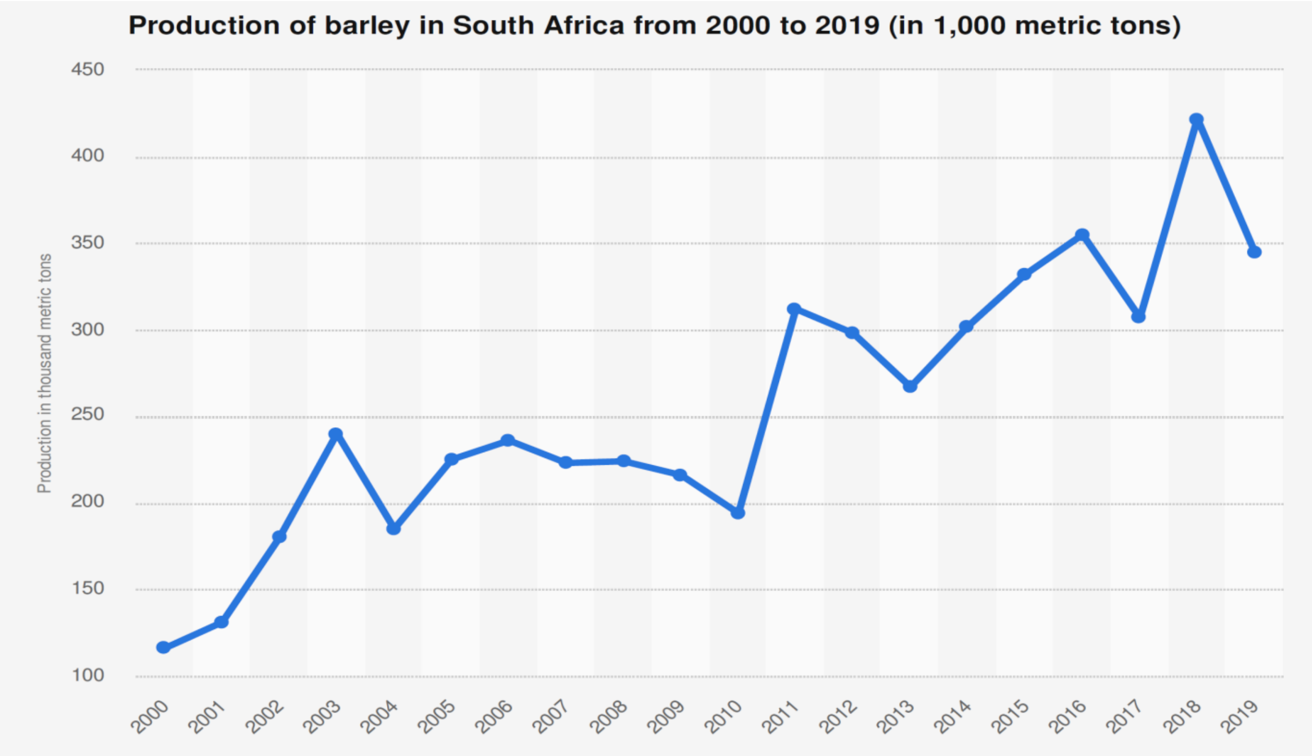


Figure 2.7 - The production of barley in South Africa from 2002 until 2019, measured in 1000 metric tons (Source: Galal, 2021).

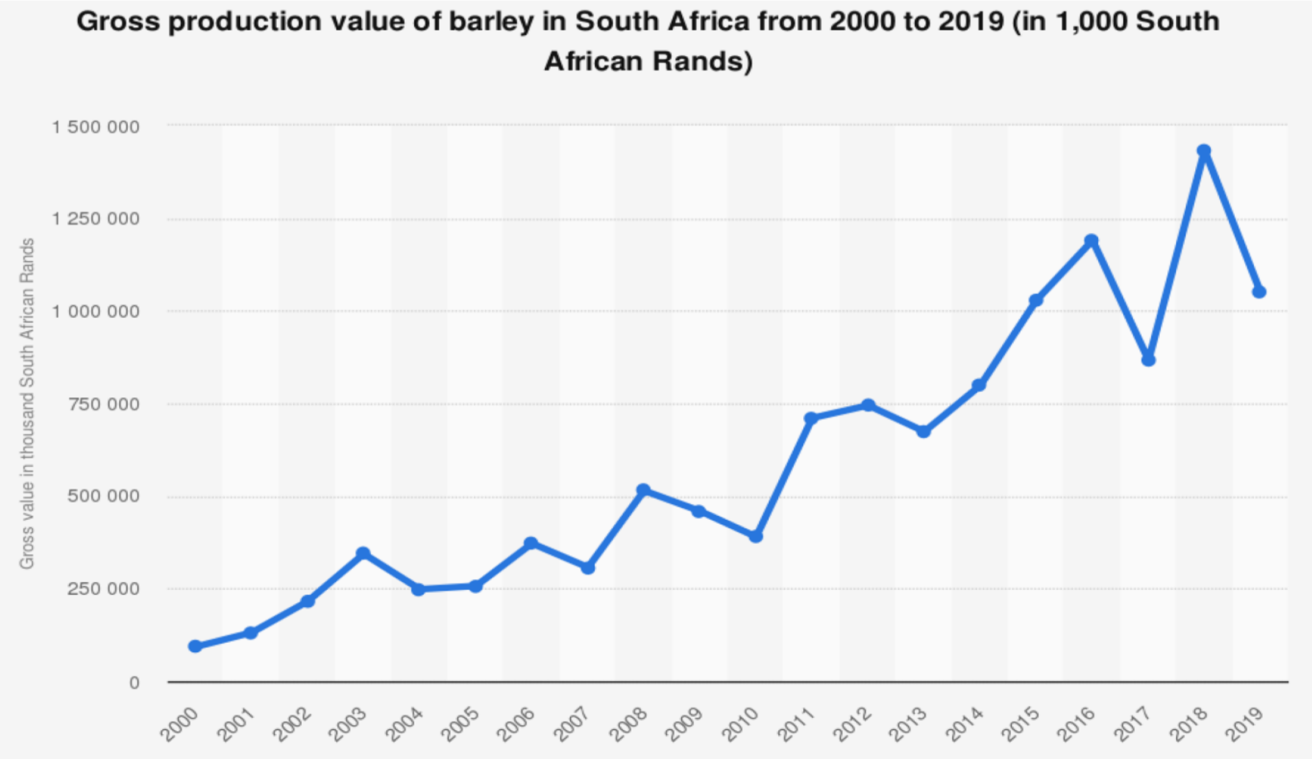


Figure 2.8 - The gross production value of barley in South Africa from 2000 until 2019, measured in 1000 South African Rands (Source: Galal, 2021).

The local demand for barley in SA is higher than the local supply. On average, the annual commercial production of barley is about 272 300 tons, whilst the average annual consumption of barley in SA is 295 576 tons of barley (DAFF, 2017). It is difficult for barley producers in SA to meet this demand as most of the country is unsuitable for barley production as only a small area of SA is a winter rainfall area (needed for dryland barley production) and barley in all other regions would need to be grown under irrigation. To meet the demand, SA imports an average of between 46 and 121 thousand tons of barley per annum. Variable rainfall and droughts have caused fluctuations in barley yields and quality in SA over previous years and when the local crop is unable to meet the local demand, barley is imported, mainly from Canada, but to a lesser extent from the EU and Australia (DAFF, 2017). South Africa does not impose any import tariffs on barley imports and in turn, does not face any tariffs when exporting barley.

The main uses of barley in SA includes the production of malt, used in the brewing of beer, whilst a smaller quantity of lower quality barley is used for animal feed. Most of the barley is planted for malting purposes rather than for use as animal feed due to the large quantities of maize produced in SA which is a more popular option for animal feed. Unlike other South African agricultural commodities, barley producers are limited mainly to one large buyer, namely the Belgian-based multinational beverage and brewing company Anheuser-Busch InBev (AB InBev) (Gilbert, 2018). This major buyer was previously South African Breweries Maltings (SABM), but is now AB InBev and supplies its major stakeholder, South African Breweries, with malted barley (DAFF, 2017). Due to there being one major buyer of barley in SA, local producers are guaranteed a market for their produce and have fixed price contracts with the buyer.

2.6.5) Canola Production

Canola is an oilseed crop mainly grown in the Overberg area of the Western Cape Province of South Africa. This area of the Western Cape is considered the commercial hub of canola production in the country (Sihlobo, 2018). The Western Cape is responsible for 99.8% of South Africa's canola crop, which in turn makes up approximately two thirds of canola seed production in Africa (Sihlobo, 2018). In 2019, 74 000 hectares of canola were planted in South Africa, producing an estimated 96 000 tons to the gross value of approximately R529 437 000, as illustrated in Figures 2.9 and Figure 2.10 (DAFF, 2020).

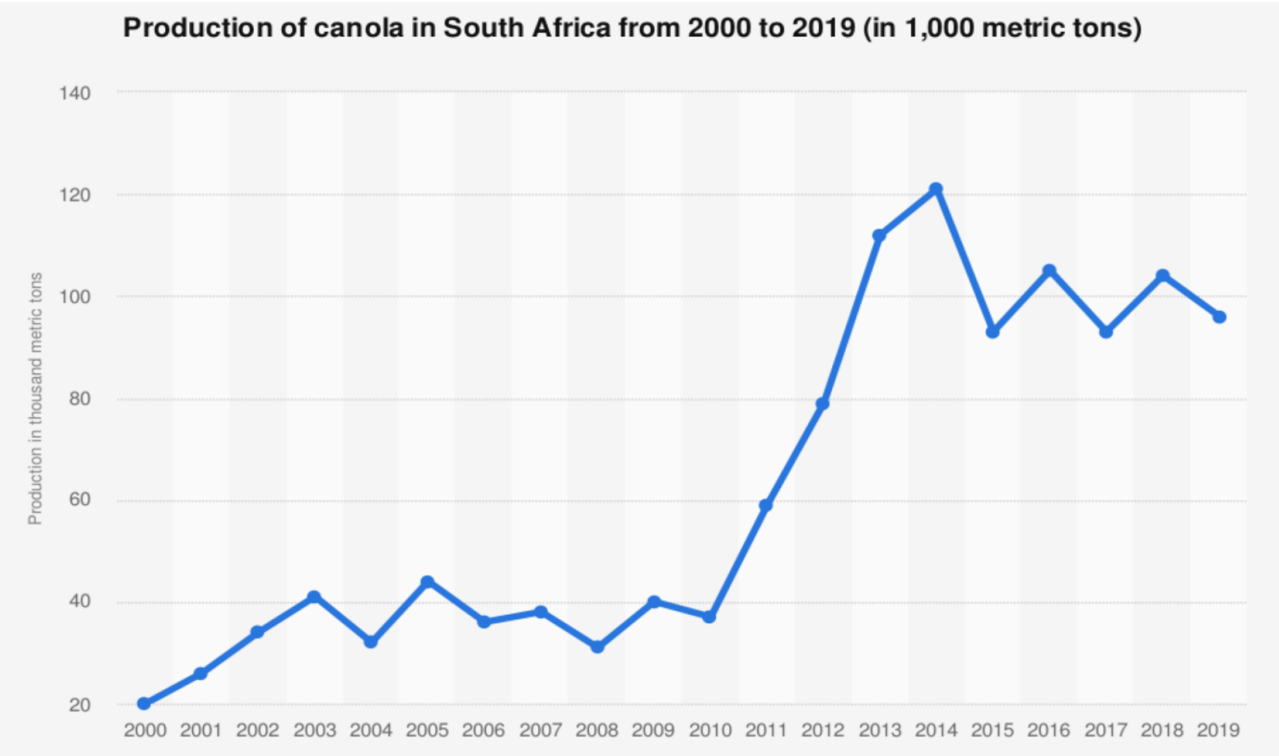


Figure 2.9 - The production of canola in South Africa from 2002 until 2019, measured in 1000 metric tons (Source: Galal, 2021).

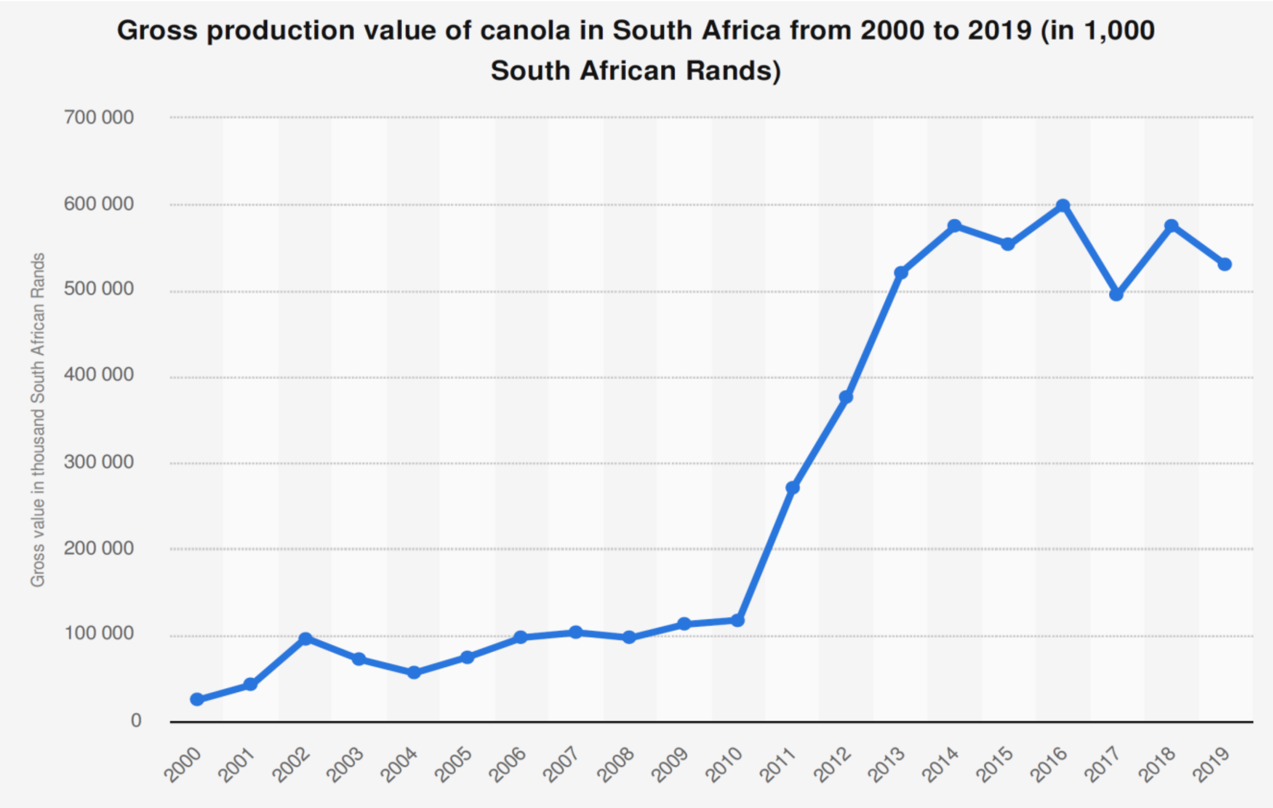


Figure 2.10 - The gross production value of canola in South Africa from 2000 until 2019, measured in 1000 South African Rands (Source: Galal, 2021).

Local canola production in SA is generally sufficient to meet local demand. On average, about 62 000 tons of canola are processed annually in the market in SA, while local production is an average of 65 000 tons per annum. However, due to fluctuating levels in canola production, due to climate and other factors, SA has been a net importer of canola for the past 10 years. SA exports an average of 15.37 tons of canola annually and imports and average of 130.65 tons per annum (DAFF, 2016a). The majority of the canola exports from SA are to other African countries, however, these exports are small quantities and usually do not exceed 45 tons annually. SA imports canola mainly from Europe and Oceania, with minimal African imports (DAFF, 2016b).

The primary use of canola is the production of canola oil, which is used for human consumption and is commonly used for cooking purposes. A by-product of canola oil processing is canola meal, which is a high protein ingredient often used in animal feed. Canola meal can also be used as a fertiliser, especially in organic farming (DAFF, 2016a).

Canola is also of great economic value when used in crop rotation systems, and the use of canola instead of small grain crops has become increasingly popular in the Western Cape (DAFF, 2016b). Herbicide resistant cultivars of canola allow for the combination of wheat and canola in crop rotation systems to be beneficial in many ways. One benefit is that canola usually causes higher yields for consecutive crops, for example, yield increases of up to 25% have been found when wheat is planted after canola in a crop rotation system (Hoffmann, 2010). Due to canola being a broadleaf crop, different herbicides can be applied to those that would be applied to a grain crop and this reduces the increased resistance of weeds to specific herbicides and helps with weed control in crop rotation systems (Hoffmann, 2010).

2.6.6) Oats Production

The production of oats in SA takes place mainly in the winter rainfall area of the Western Cape, as oats are a winter crop. The Western Cape produces approximately 90% of South Africa's oats due to the suitable climatic conditions in the province, with smaller quantities being grown in the Northern Cape, Free State and Eastern Cape (Sihlobo, 2018). An estimated 82% of oats produced locally in SA are used to make human consumables. It can be rolled/crushed into oatmeal or ground into a fine oat flour. Oats are also used in cereals and consumed raw (DAFF, 2016c). Ten percent of the local oats supply is used for animal feed, primarily for cattle and horses. Oat straw is also used as bedding for animals in some instances. The remaining 8% of the local oats supply is used by seed companies to produce seeds for planting (DAFF, 2016c). Oats are also popular for use as a grain crop in crop rotations systems (Hoffmann, 2010).

South Africa produces an average of 39 000 tons of oats per annum whilst the local consumption is higher at 46 000 tons per annum. In order to meet the local demand for oats, SA imports an average of 22 000 tons per year, most of which is from Australia (DAFF, 2016c). The average local oats production of 39 000 tons per year contributes an estimated R 80.74 million to the agricultural GDP per annum. A very small portion of oats produced by SA, approximately 813 tons, are exported annually to the value of about R8.32 million per annum. These exports are mainly to other African countries, with a small amount going to Asia. South Africa applies no import tariffs on oats, but does face tariffs when exporting oats (DAFF, 2016c).

2.6.7) Lucerne Production

Lucerne (*Medicago sativa*), also known as alfalfa, is a perennial legume pasture which is well-adapted and can perform in many areas of South Africa, provided there is sufficient water availability (Agricol, 2016). In the Western Cape, lucerne production is mainly limited to the Overberg region, as the other major grain producing area, the Swartland, is too hot and dry during summer (Hoffmann, 2010). The wide adaptability of lucerne is mainly due to its deep root system, allowing the plant to draw water from deeper soil levels, thereby allowing it to persist in drier climates (De Kock, 2012). Lucerne is mainly used as a fodder crop for livestock and is known to be a highly successful cultivated crop for this purpose. This success can be attributed to its deep, highly efficient root system, coupled with its symbiosis with the nitrogen-fixing rhizobium bacteria which reduces the plant's dependence on soil nitrogen (NLT, 2018). An advantage of lucerne being able to effectively fix nitrogen in the soil, is that cash crops planted afterwards will be able to utilise this nitrogen which can then cause yield increases and lessen the need for chemical inputs (NLT, 2018).

In South Africa lucerne is mostly grazed directly but can be baled when higher rainfall allows for higher yields. There is also a market for lucerne seed. In the 2017/18 season, 620 tons of seed were produced, to the estimated gross value of R50 803 000. Approximately 1 376 000 tons of lucerne hay were produced in the 2017/18 season, to an estimated gross value of R 4 154 101 000 (DAFF, 2019). The use of lucerne hay has become increasingly popular as an ingredient in animal feed, due to its crude protein content. This demand for feed may continue to drive the expansion of the lucerne market in South Africa and globally (MI, 2020). The lucerne market in SA is highly fragmented and includes both domestic small and medium scale players but is efficient and functional.

It is estimated that in 2018, SA exported approximately 106 000 tons of lucerne to countries such as Saudi Arabia, United Arab Emirates, Botswana, China and others (MI, 2020).

Lucerne is also used in crop rotations in many areas of SA, often in long pasture crop rotation systems in the Overberg with great success if grazing is managed correctly (Hardy, 2004).

2.6.8) Medics Production

Medics (*Medicago* spp) is mainly used as a pasture crop and is known to re-establish itself if properly managed (Hoffmann, 2010). Annual medics and clover pastures are mainly used in annual rotation with grain crops in a short rotation system (Hardy, 2004). Medics is also capable of nitrogen fixation in the soil and grain crops planted after medics in a crop rotation system often show higher yields. Medics also assists with pest and disease control in subsequent crops in a crop rotation system (Hoffmann, 2010). Ultimately, the production of medics and clovers are likely to reduce input costs and increase yields of subsequent crops (Basson, 2017).

Medic and medic/clover pastures provide high quality fodder to sheep in winter months and medic residues and mature pods are also grazed by sheep during the summer months (Hardy, 2004). Due to the high-quality feed produced by medics, they can be considered a catalyst for livestock production and allow for livestock to be incorporated into crop-pasture systems as part of a crop rotation system (Basson, 2017). In South Africa, lucerne and annual pasture legumes such as medics are well suited to areas such as the Overberg, due to its winter rainfall. These pastures are known to contribute to organic matter in the soil (Basson, 2017), thereby improving soil quality for subsequent crops. These legumes can fixate nitrogen from the air and medics and clover pastures have been estimated to fix between 40-100 kg of nitrogen in the soil per hectare (Herridge, 2014).

2.6.9) Lupine Production

Lupine is an annual legume which is known to have a high protein content and can be used directly for grazing or as an ingredient in animal feed (Hoffmann, 2010). Areas in South Africa where lupines are mostly found are the Western Cape, Free State and North West provinces (DAFF, 2011). Lupines perform best in winter rainfall areas, such as the Overberg area of the Western Cape. Approximately 20 000 hectares of lupines are planted annually, the majority of which is in the Western Cape.

Lupines are often used in crop rotation systems, due to some key functions that they can perform. These include nitrogen fixation from the air as well as soil amelioration (Basson, 2017). The nitrogen fixing ability of lupine will reduce input costs by lowering the nitrogen requirements of the subsequent crop. The improvement in soil structure and lower soil densities following a lupine crop, will increase the yields of the subsequent crop. There is no stable market for lupines in South Africa and this is a challenge for many lupine producers.

2.6.10) Triticale Production

Triticale is a versatile crop and is mainly used by livestock farmers for animal feed, however it can also be used as a forage crop and cover crop (ARC, 2020). There is limited demand for triticale in SA and due to this, the price for triticale is derived from the price of feed-grade maize, as triticale is often used as a substitute for maize in animal feed (Roux & Marais, 1996). There has been an interest in using triticale for bio-ethanol production, however this is still an emerging field. Triticale has been seen to be more disease-resistant than wheat which may be due to the limited amount of triticale currently being planted in SA (Hoffmann, 2010). The Overberg has a large area of marginal soils and triticale has been found to be well suited for these soils, more so than wheat. The planting of triticale instead of wheat on these marginal soils is expected to increase as the demand for triticale as a substitute for maize in animal feed increases (Roux & Marais, 1996).

2.7) The Overberg

2.7.1) Introduction to the Overberg

The Overberg region of the Western Cape is situated in the southernmost area of South Africa. The Overberg lies to the South-East of Cape Town and stretches from the Hottentots-Holland Mountains in the west to the Breede River mouth in the east, and as far as the Riviersonderend Mountains in the north. The major towns in this region include Grabouw, Hermanus, Caledon, Swellendam and Bredasdorp and the region covers approximately 12 241 km^2 (WCG, 2020).

Approximately 448 269 hectares of this region are under crop production. Of these, 391 785 hectares are under dryland production and 27 009 hectares are under irrigation (WCDA, 2020). Rain fed small grain production is a major part of the Overberg's agricultural endeavours. The predominant grain crops include wheat, barley, oats, triticale and canola which are all cash crops and often form part of crop rotation systems in the area. Wheat is the most widely produced and approximately 65 475 hectares are planted to wheat in the Overberg region, with 43 412 ha being planted to barley and 36 408 ha being planted to canola (Department of Rural Development & Land Reform, 2017).

2.7.2) Map of the Overberg

Figure 2.11 below shows the geographical boundaries of the Overberg District within the Western Cape province of South Africa.

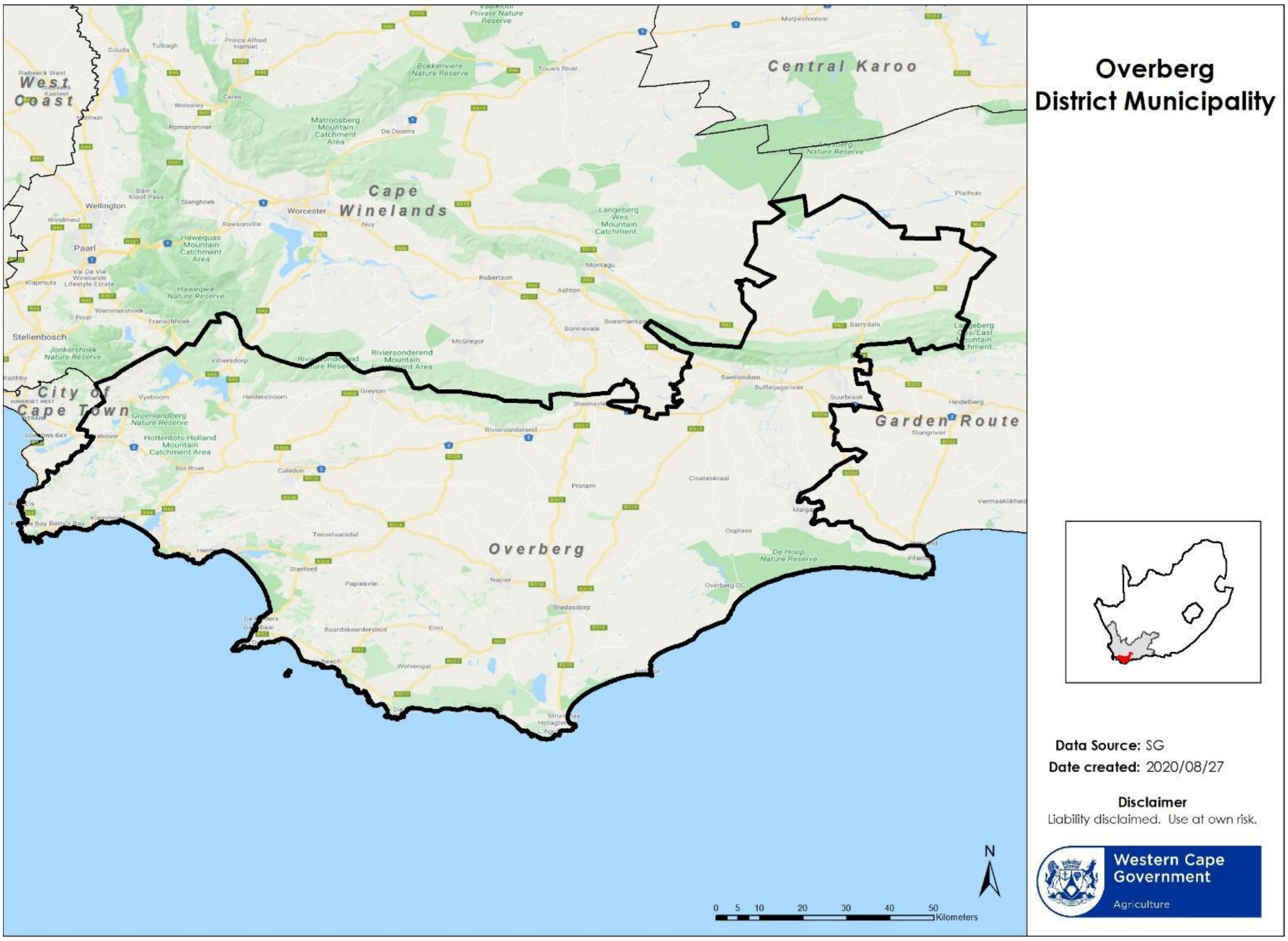


Figure 2 11 - Map showing the Overberg region in the Western Cape Province of South Africa (Source: Liezl Mackenzie, WCDA GIS services, 2020).

2.7.3) Cultivation in the Overberg

There are two main winter cereal production regions in the Western Cape, namely the Swartland, towards the West Coast and the Overberg in the more southern region of the Western Cape (Hardy, 2007). The Western Cape is known for its Mediterranean climate with cold, wet winters and hot, dry summers. However, the province is also known for unpredictable fluctuations in temporal and spatial distribution and amount of rainfall (Hardy, 2007). The major difference between the Swartland and the Overberg is the proportion of winter to summer rainfall - it is this which dictates the crops that can be grown in the regions. The Overberg has a milder, more temperate climate than the Swartland and receives between 75% (in the Western parts) and 55% (in the Eastern extremities) winter rainfall. Due to the higher proportion of summer rainfall in the Overberg, crops such as lucerne can grow, as well as crops such as medics and lupines, which are more difficult to cultivate in the Swartland.

There are higher risks associated with winter cereal production in the Overberg. This is due to the higher proportion of summer rainfall in the region which increases the chances of lower rainfall during the winter growing season (Hardy, 2007). Although there are more risks associated with rainfall in the Overberg, the higher proportion of summer rainfall and the milder climate allow for a more rapid breakdown of organic matter which adds to the carbon pool of the soils, providing healthier soils in which to grow crops (Hardy, 2007). In both areas, pasture crops are used as a necessary break from grain production in many crop rotation systems and they allow for the integration of livestock into these systems.

2.8) CA adoption

2.8.1) CA adoption in South Africa

South Africa is regarded as a mostly semi-arid country, severely limiting the area of arable land suitable for cropping. Due to the harsh conditions in many parts of the country, more sustainable farming methods are being promoted for the future, as current conventional practices have been seen to cause major soil degradation and erosion. CA has been put forward as a more sustainable farming method for the future in South Africa but has seen slow adoption rates in most areas of the country. An exception is the Western Cape which has a dry, Mediterranean climate and farmers in this area are more readily adopting CA practices.

The first CA research trials in South Africa were done in 1976 in the maize growing areas and were conducted by the Small Grains Institute of the Agricultural Research Council (ARC) of South Africa (Mudavanhu, 2015). CA research trials continued into the 1980s and 1990s, but South African producers were still sceptical about CA adoption. The main hindrances to CA adoption were outlined by Knott (2015) as:

- Lack of competent tillage equipment
- Costly herbicides and pesticides
- A decrease in yields and quality due to disease build-up
- No-tillage being tested on fields that already had issues
- Farmers not being open to changing their mind-sets

The deregulation of South Africa's wheat and maize industry in the 1990's saw a decrease in producer prices, forcing farmers to seek new ways of reducing their input costs in order to remain competitive at the global level (Kooper, 2020). CA had been found to reduce input costs in other parts of the world and thus became a more appealing ideal to many grain farmers in South Africa, as it was a more ecologically and economically sustainable option.

CA was mainly being adopted by larger scale, commercial farmers in the 1990s whilst smallholder farmers were slower to adopt the practice. Since 1997, the South African government has partnered with research institutions (such as the ARC) to promote CA interventions under the umbrella term of community-based natural resource management programmes. Examples of this are LandCare (under the Department of Agriculture, Forestry and Fisheries; DAFF), Conservation Agriculture Technologies (under the Department for Rural Development and Land Reform) and Eco-Technologies (also under DAFF), all of which are aimed at uplifting smallholder farmers and promoting CA within their farming environments (Swanepoel *et al.*, 2017). Since 2010, the grain industry (mostly the Maize Trust (MT) and Winter Cereal Trust (WCT)) have increased their support for CA research. In 2014 the CA Farmer Innovation Programme was established by MT, WCT and GrainSA to promote CA research projects and knowledge sharing between large- and small-scale grain farmers.

South Africa is the leader for CA adoption on the African continent with the largest land area under CA. The area under CA in South Africa increased from approximately 368 000 ha in 2008/9 to an estimated 439 000 ha in 2015/16 (Kassam *et al*., 2018). The areas with the most land under CA are mainly in the Western Cape, Kwa-Zulu Natal and Free State provinces where it has been adopted by sugarcane and grain farmers (Mudavanhu, 2015). The province with the highest uptake has been the Western Cape and this is said to have been mostly farmer and market driven (Knott, 2015). No-tillage clubs have also been formed in both the Western Cape and Kwa-Zulu Natal which are essential for the gathering of knowledge regarding CA (Kooper, 2020).

Climatic conditions vary throughout South Africa, creating a landscape with very different agricultural systems in different areas. There is also a wide range of tillage practices being used across the country. It is estimated that only 20% of cropland in South Africa is under only conventional tillage whilst the remaining 80% is under varying tillage practices, ranging from no-tillage to conventional till (Knott, 2015). Factors slowing the adoption of CA in South Africa include socio-economic constraints, insufficient soil cover in many areas, the current traditional land tenure and uncontrolled communal grazing (Kooper, 2020).

2.8.2) CA adoption in Western Cape

The adoption rate of each of the three principles of CA is above 40% in South Africa however, only 14.2% of farmers adopted all three principles concurrently (Findlater *et al.*, 2019; Strauss, 2021). This is not evenly distributed over the whole country - the Western Cape Province has by far the highest CA adoption rates in South Africa (Swanepoel *et al*., 2017). The Western Cape is a major grain producing area of South Africa and is known for its unique Mediterranean climate with hot, dry summers and cold, wet winters. Within the Western Cape there are two main grain producing regions, namely the Swartland and the Overberg. The main distinction between these regions is that the Swartland receives very little summer rainfall whilst the Overberg can receive up to 40% of its annual rainfall in the summer months, making it a somewhat less harsh grain producing region.

Wheat is the largest winter grain cereal produced in the Western Cape and plays a major role in the food security of South Africa as it is a staple food. In the 2017 planting season, the Western Cape produced an estimated 66% of the total amount of commercially produced wheat in SA and approximately 87% of the wheat produced in the Western Cape comes from either the Swartland or the Overberg (Kooper, 2020). South Africa remains a net importer of wheat as the local supply is not sufficient to meet the local demand.

Wheat was traditionally planted as a monoculture crop in the Western Cape, but this led to serious soil erosion and loss of soil fertility which negatively impacted yields (ARC Economic & Biometrical Services, 2014). There was a need for a more sustainable cropping method and CA was put forward as a proposed method of doing this by the Agricultural Research Council (ARC) and the Western Cape Department of Agriculture (WCDA). Two long-term research trials were set up by the WCDA, one starting in 1996 and the other in 2002, to assess the effects of no-tillage, residue management, crop rotation and livestock integration on the sustainability of an agricultural production system in the Western Cape (WCDA, 2015). In recent years, the Conservation Agriculture Association of the Western Cape (CAWC) was launched as a forum to share knowledge between researchers and farmers on context-specific issues. The aim of the CAWC was to bring researchers, industry, producers and government together so they can work to strengthen and advance CA practices in the Western Cape (WCDA, 2015).

It is estimated that 75 to 80% of grain producers in the Western Cape use some form of CA. Farmers have adopted CA to varying degrees but according to Dr Johann Strauss at the WCDA, approximately 90% of grain farmers practice no-tillage, about 90% use crop rotations and an estimated 65% maintain permanent organic soil cover (WCDA, 2015). The strong research base for

CA in the Western Cape has shown many benefits of adopting the practice. In 2013 the ARC conducted an impact study on wheat farmers who had adopted CA technology and it was reported that 84% showed an increase in total wheat production while 93% reported an increase in total income per hectare, 70% of farmers also reported a marked decrease in labour costs (ARC Economic & Biometrical Services, 2014).

Although there is evidence of many positive benefits of adopting CA, there are also constraints to CA adoption in the Western Cape. A substantial initial capital investment is needed to start the move to a CA system as new equipment is needed and this is a particular challenge for many farmers in the Western Cape. CA is a very knowledge-intensive practice and requires patience as benefits may take years to appear, especially in the harsh conditions of the Western Cape. CA also needs to be done in combination with other good practices such as integrated nutrient, pest, water and weed management in order for the true benefits of CA to be realised (WCDA, 2015).

CA adoption rates continue to increase in the Western Cape as support for the practice grows. This increase in adoption is facilitated by the support and research from the ARC and the WCDA. The ARC developed a robust no-tillage planter, suited to the sandy, rocky conditions of the Western Cape which was a great help to producers converting to CA. Other technologies adapted by the ARC specifically for the Western Cape included the introduction of pre-plant herbicides to control herbicide resistant ryegrass (ARC Economic & Biometrical Services, 2014). Both the WCDA and CAWC are also committed to assisting farmers making the transition from conventional to CA farming.

The Western Cape Department of Agriculture (WCDA) outlined factors which were found to either enable or hinder the uptake of CA in the Western Cape (WCDA, 2015) as shown in Table 2.2.

Table 2.2 - The following factors were identified as either enabling or hindering the uptake of CA in the Western Cape.

Enabling Factors	Hindrances
• The reduction of input costs as a motivating factor	• The focus on short-term rather than long-term benefits by local farmers
• Research and leadership from the WCDA	• Farmer’s assumption that cover crops will not bring in any money.
• CAWC outreach	• Machinery costs as CA equipment can be expensive
• Affordability & availability of no-tillage machinery, suited to the shallow, rocky soils of the WC	• Mind-set change needed by farmers to apply and trust a completely new approach
• Cooperation between researchers, government, industry and farmers	• The knowledge intensity of CA
	• The adoption of the new weed management approach required by CA

2.8.3) Conservation Agriculture in the Overberg

Rain fed small grains, canola and lucerne production occurs mostly in the Cape Agulhas and Swellendam regions of the Overberg which are on the southern side of the Langeberg mountain, which has a much higher annual rainfall than the Klein Karoo side of the Langeberg mountain, making it more suited to annual crop production (Department of Rural Development & Land Reform, 2017). This region of the Western Cape has been a major grain producing region for many years. Initially monoculture was the predominant method of grain production in the area (Hardy, 2007), but more recently alternative, more sustainable cropping methods are being adopted by many farmers in the area. Monoculture practised over a long period of time, seriously degrades soils and allows for the proliferation of many soil pathogens which results in lower crop yields (Department of Rural Development & Land Reform, 2017).

As farmers realised monoculture was non-sustainable, both economically and biologically, many started adopting conservation agriculture practices, such as using crop rotation systems. Approximately 70% of grain producers in the Western Cape make use of CA practices (GreenCape, 2019). The three pillars of conservation agriculture include crop rotations, minimum tillage and permanent soil cover and/or cover crops. Some farmers choose to use only one or two CA practices, whilst others use a combination of all three. There are still divided opinions on the use of CA, however, many farmers are beginning to adopt CA practices and are seeing favourable results such as better soil health and higher yields (Modiselle & Verschoor, 2015).

There are still many challenges associated with the adoption of CA in the Western Cape, one of which is that in many areas, where livestock graze stubble post-harvest, there is still not sufficient soil cover to be considered true CA farming (Swart, 2013). This issue has caused several grain farmers in the Overberg to remove livestock from their cultivated fields. The shift from conventional tillage to minimum tillage has also been a challenge as many farmers still believe in using conventional ploughing implements and practices.

There have been arguments for and against the widespread adoption of CA in the Western Cape, but from the growing evidence it is shown that CA is a good option for sustainable grain production in the Western Cape (Swart, 2013). Although CA is being practiced in the Overberg there is always room for improvement and growth and as the positive results of CA become more apparent it is expected that more farmers will start to adopt CA practices. CA is shown to have many biological and economic benefits and will contribute to the long-term sustainability of agriculture in the future.

2.9) Crop Systems in the Middle Rûens

The Middle Rûens is situated in the Overberg region in the southern part of the Western Cape Province of South Africa. The experimental trials that will be focused on in this project are situated on a research farm (Tygerhoek experimental farm) in the Middle Rûens area. This region is a winter rainfall region but falls within the Overberg which is known to also receive a proportion of summer rainfall which can be up to 55% in the more eastern regions (Hardy, 2007). The Overberg is one of two major grain producing areas in the Western Cape and mostly comprises of dryland cropping systems.

Typical farming systems in the Overberg include both crop and pasture rotations. Six-year crop and pasture rotations are commonly practised (Smith *et al.*, 2020). The crop systems are usually limited to only a few different crop types. These are wheat, barley, canola, Lupines, triticale, medics, lucerne and some other cover crop varieties. These crops can be grown in different sequences in crop rotation systems but in terms of crop variety, the environment is only suitable for the above-mentioned crops. The research trials at Tygerhoek experimental farm in the Middle Rûens are designed to mimic a typical farming system in the Overberg. Therefore, the only crops included in the trials are those listed above, as these are the most commonly cultivated crops in the area.

2.10) Conclusion

Increased population growth and climate change are highlighting the need for more sustainable farming methods going into the future. A new, more efficient, and reliable approach is needed instead of modern-day conventional agriculture. Conservation agriculture has been put forward as a more sustainable method of farming that can improve the resiliency of farming systems and make better use of natural resources in the food production sphere. CA has three main principles, namely, no- or minimal-tillage, permanent organic soil cover and the use of crop rotations to improve diversity within the farming system.

Chapter 2 discusses the benefits and challenges of adopting CA. Whilst CA is said to improve overall soil health, decrease soil degradation, increase yields, and reduce input costs there are also a few drawbacks. The first few years of CA adoption may be tough on the producer financially as the potential benefits of CA can take time to come to fruition. Producers will also need guidance and support as CA is a knowledge-intensive process that requires one to be informed about the associated practices. CA is gaining popularity and has been adopted to varying degrees around the world.

The Western Cape Province is at the forefront of CA adoption in South Africa. With its unique, Mediterranean climate, the Western Cape is an area within which CA can reach its full potential, providing many benefits to local farmers. The Swartland and the Overberg are the biggest winter grain producing regions in the Western Cape and are known to produce crops such as wheat, barley, canola, oats, lucerne, medics, Lupine and triticale. These crops are often grown in rotation systems which usually include a pasture element and livestock, mainly sheep. This thesis focuses on data from an experimental farm in the Overberg region. There has been a high rate of CA adoption in this area and the use of crop rotations are commonplace. The use of CA is aimed at promoting the long-term sustainability of farming systems in the area.

The following chapter describes in greater detail, the experimental trial and data that will be used for this thesis.

Chapter 3 – Trial Design & System Layout

3.1) Introduction

The main objective of this study is to determine the critical drivers for the long-term sustainability of different crop rotation systems for the Middle Rûens area of the Overberg. This study will use existing crop rotation trial data from Tygerhoek Experimental Farm, which is run by the Western Cape Department of Agriculture and is located near Riviersonderend in the Overberg region. These trials aimed to assess the potential of various crop rotation systems within a conservation farming framework. Tygerhoek is in a homogenous area known as the Middle Rûens which is a winter grain production area. The trials were started in 2002 and have been managed according to conservation agriculture principles with minimal soil disturbance and leftover crop residues following harvesting. Tygerhoek has the physical and biological characteristics of a typical farm in the Overberg. The data collected from these trials includes climatic data and soil profiles, all input costs, yields and prices of crops for each year and all livestock information.

This chapter provides a more detailed description of the geographical location of Tygerhoek, followed by an overview of the trial itself and the different crops involved. The specific rotation systems used in the trial will then be discussed as well as the layout of the trial. An explanation of the financial information captured each year during the trial will be given, concluding this chapter.

3.2) Geographic Location of Tygerhoek Experimental Farm

The experimental trial site was situated on Tygerhoek experimental farm near Riviersonderend in the Overberg area of South Africa (34° 09' 37.7"S 19° 54' 15.4"E) as shown in Figure 3.1. This particular part of the Overberg is known as the Middle Rûens which is a homogenous farming area known for dryland production of cereal crops such as wheat, barley and canola, among others. A map showing the location of the Middle Rûens in the Overberg can be found in Appendix 2. This area has a Mediterranean climate with an average annual rainfall of 450 mm, the average rainfall during the growing season (April to October) is about 315 mm (Habig *et al.*, 2018). The exact rainfall figures are further detailed in Chapter 4. Tygerhoek experimental farm has an elevation of between 200 and 300m above sea level. The soils in this region are generally classified as Swartland, Mispah and Glenrosa which are derived from shale mother material, predominantly that of the Bokkeveld group (Vorster, 2015; Habig *et al.*, 2018). These soils are usually rather poorly developed and very shallow. Tygerhoek was established in 1960 and covers 2760 ha of which an estimated 500 ha is arable land (“Tygerhoek Research Farm”, 2021).

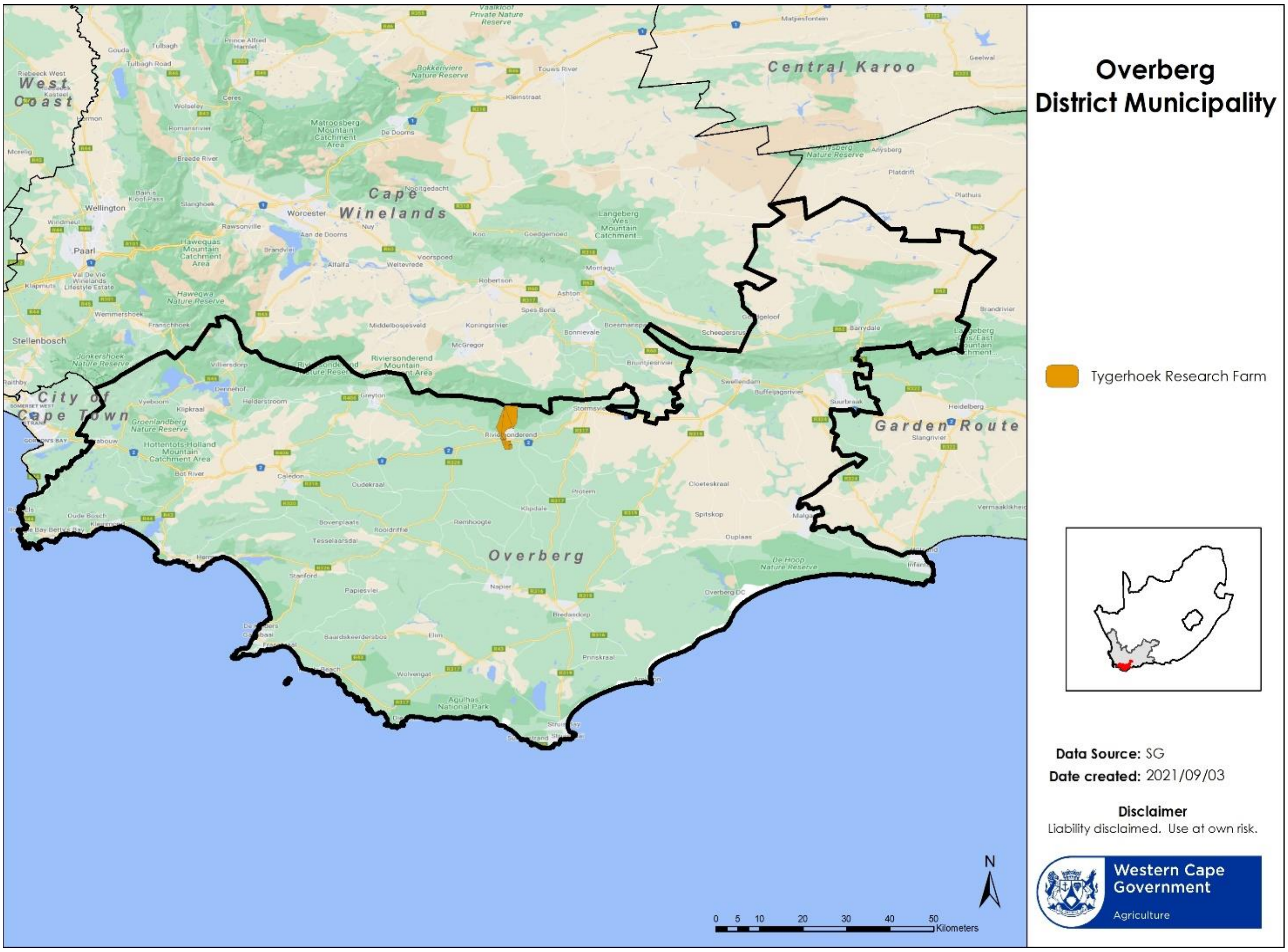


Figure 3.1 - Map showing the geographical location of Tygerhoek Experimental Farm within the Overberg region of the Western Cape (Source: Liezl MacKenzie, WCDA GIS services, 2021).

3.3) Trial

3.3.1) Overview

Tygerhoek is one of three trial sites in the Overberg that form part of one main project. Tygerhoek focuses on short crop rotation systems whilst the other two sites (Riversdale and Swellendam) focus on long rotation systems. The reasons for initiating the main project included a lack of knowledge on 1) the short- and long-rotation systems that could be used to bring about and maintain the economic and biological sustainability of crop production systems in the Overberg and, 2) the primary (internal and external) economic and biological components supporting sustainability within these production systems (Strauss *et al.*, 2012). The project co-ordinators for the Tygerhoek trial site are Dr Johann Strauss and Willie Langenhoven, both of whom are associated with the Western Cape Department of Agriculture. This study focuses exclusively on the data from the short rotation trials at Tygerhoek.

The aim of the Tygerhoek trial, was to determine the sustainability of different short crop rotation systems in the Overberg. The Tygerhoek trial was initiated in 2002 and is still in progress. For this study, trial data collected between 2002 and 2020 was used.

The experimental layout used was a randomised block design with each year having two replicates of each rotation treatment. These rotations were either continuous cash cropping rotations or a mix of different cash crops in combination with pasture years. During the pasture phase of the crop/pasture rotation systems, the camp size was 2 ha, which provided adequate space for enough livestock (sheep) to obtain reliable lamb and ewe performance data. During the cropping phase of the rotation systems, the pasture camps are divided into 0.25 ha sub-camps, each of which is dedicated to a specific crop or crop/pasture cycle for the duration of the experiment. There are 108 sub-camps in total on this trial site.

All treatments are managed according to a conservation farming approach which included minimum- and no-tillage land preparation and planting as well as the retention of crop residues after harvesting. However, the systems including a pasture phase allowed for the crop residues to be used as grazing for sheep during the hot, dry summer months. To accommodate the effects of climate and commodity price fluctuations on crop yields, all phases of each rotation system are present each year. For example, the rotation system PPO (pasture-pasture-oats) will have all possible crop sequences present each year, these include; an oats year after two consecutive pasture years (PP<u>O</u>), first year pasture after oats and one pasture year (PO<u>P</u>) and second consecutive year of pasture following oats (OP<u>P</u>).

Chapter 3.4 gives a more detailed description of the specific crop rotation systems and trial layout on Tygerhoek.

3.3.2) Crops

The following crops and pastures were used in the different crop rotation systems on Tygerhoek Experimental Farm.

3.3.2.1) Wheat

Wheat (*Triticum aestivum*) is considered to be the most important small grain produced in South Africa, following maize (“Winter Cereal Trust”, 2021). It is believed that wheat originated in the Near East, the countries now known as Turkey, Syria, Afghanistan, Iraq and Iran. Archaeological remains of wheat have been found from as far back as 6500 BC (DAFF, 2016d). Wheat was first planted in

South Africa in 1652 when Jan van Riebeeck settled in the Cape (Jordaan, 2002).The main wheat producing provinces are the Western Cape, Free State and Northern Cape. The south western parts of the Western Cape (Swartland and Rûens) are the main wheat producing regions in the province and wheat is planted as a winter cereal with a growing season from April to October each year. Factors such as cultivar choice and rainfall are the main determinants of wheat yields. Winter wheat is tolerable of the cooler temperatures (5 ºC to 25 ºC) found in the Overberg area, where the experimental trials for this study were situated (DAFF, 2016d). The average rainfall requirement for wheat is about 600 mm annually, but in dryland production areas, where no till and crop residue retention are practised, good yields can still be achieved with slightly lower rainfall due to the improved moisture retention of the soil (DAFF, 2016d).

3.3.2.2) Barley

Barley (*Hordeum vulgare*) is the second most important small grain produced in South Africa, following wheat (ARC, 2019). The cultivation area for barley under dryland conditions is restricted to a very specific region in South Africa, namely the Overberg. Barley is a winter cereal crop and is often included in crop rotation systems in the Overberg, with the aim of improving the resiliency and stability of the farming system (DAFF, 2017). The Western Cape is the biggest barley producing province in South Africa, with the majority of the barley being produced in the Overberg region of the province (Kooper, 2020). Barley in SA is mainly produced for malting purposes with only the lower-quality barley being used in animal feed. Cultivar choice has a major impact on barley yields and is a very important economic choice for the producer, as it will affect the overall profitability of the crop (ARC, 2019). Malting companies have a preference for barley from the Overberg in particular, due to the unique protein and starch qualities of the barley from this area (Kooper, 2020).

3.3.2.3) Canola

Canola (*Brassica napus L.*) is an oilseed crop, originating from rapeseed which has been found to date as far back as 3000 years ago (DAFF, 2016a). Canola can be grown as both a summer and winter crop, but is mainly grown as winter crop in the Western Cape in South Africa. For good yields, canola will need about 300 mm of rain with an even distribution over the growing period. Canola is particularly sensitive to drought conditions during the flowering and grain filling stages (DAFF, 2016b).

Canola is often used as a rotation crop, as it has a comprehensive root system known for improving soil structure, aeration and water infiltration (Knott, 2015). The inclusion of canola in crop rotation systems with wheat has been found to improve wheat yields when wheat follows canola (Hoffmann, 2010). Canola can also assist with weed control in subsequent crops, as it is a broadleaf crop which will not be affected by the chemicals used to get rid of grass weeds, a prominent weed found in wheat and barley crops. However, canola is limited to only being grown every third or fourth year in crop rotation systems, due to a disease known as blackleg (*Leptosphaeria maculans*) disease (Kooper, 2020). However, the inclusion of canola in crop rotation systems contributes to the profitability and sustainability of these systems, especially in combination with crops such as wheat and barley or pastures.

3.3.2.4) Oats

Oats (*Avena sativa*) are believed to have mainly Asiatic origins. Oats are suitable for production in all regions of South Africa due to its wide planting spectrum and adaptability (DAFF, 2010). The main purposes for oats cultivation in South Africa are grazing and hay production while there is a very limited market for oats in the breakfast cereal market in SA. Oats are also often produced for the animal feed market (ARC, 2019). In many no-tillage farming systems cover crops are used to obtain sufficient groundcover and diversity. One good option for use as a cover crop are oats, due to their broad adaptability and high biomass production (ARC, 2019). The inclusion of oats in crop-rotation systems also assists in the suppression of soil-borne diseases such as take-all (ARC, 2019). In the trials run at Tygerhoek, oats were planted for hay production in the earlier years and then used for seed production later on in the trial.

3.3.2.5) Lupines

There are three different annual lupine species grown commercially in South Africa, namely narrow leaf (*Lupinus angustifolius*), broad leaf (*Lupinus albus*) and yellow lupine (*Lupinus luteus*). The earliest reference to lupine cultivation in SA was in 1897 and by 1949 it was commonly used in crop rotation systems, especially in the Western Cape (Agenbag, 2007). Lupine can be planted in summer or winter rainfall regions and they prefer slightly acidic, poorer soil (Truter *et al.*, 2015). Lupines are leguminous plants and are known for fixing nitrogen in the soil, which is highly beneficial to the successive crops when used in a crop rotation system. Lupines can be used as a rotation crop, a silage crop or a pasture crop and are useful for soil improvement purposes (Truter *et al.*, 2015).

3.3.2.6) Medics & Clovers (Pastures)

Medics (*Medicago* spp.) and clovers (*Trifolium subterraneum* & *T. balanceae*) are used in combination as annual pastures in many areas of the Western Cape. One of the main benefits from these plants in crop rotation systems is the additional nitrogen being added into the soil by these pastures. These species have been found to contribute up to 40 – 100 kg of nitrogen per ha to the soil, 40% of which may be available to subsequent crops (Clarke, 1980). Once medics have been properly established, they usually produce enough seed to be able to re-establish the following year. If the medics are killed to allow for a “wheat-year”, there is most often an adequate seed bank which then allows the crop to easily establish again the next year. Grass weeds can also be diminished during pasture years in crop rotation systems as alternative herbicides can be used. The variety of herbicides used also reduces the occurrence of herbicide resistant grass weeds such as ryegrass. The reduced weed pressure and additional nitrogen available in the soil are highly beneficial to subsequent crops such as wheat in crop rotation systems and often increases wheat yields (Basson, 2017). The pasture phase enables the farmer to have sheep on the fields during the growing season which also assists with weed control (MacLaren *et al*., 2018).

3.4) Systems

There are five rotation systems being compared at Tygerhoek which include the following: P = annual legume mixed pasture (medics/clovers); W = Wheat; B = Barley; C = Canola; O = Oats; L = Lupines and; Luc = Lucerne. Rotation System 1 is continuous lucerne pastures but data from this rotation system will not be used for this study, only data from Rotation Systems 2, 3, 4 and 5 will be used. There are five main rotation systems, each of which has different sub-systems (e.g. 2a, 2b, 2c).

Rotation System 1: 100% Lucerne pasture (not relevant for this study)

Rotation System 2: 67% annual legume pastures: 33% crops

- 2a – PPW
- 2b – PPO
- 2c – PPB
- 2d – PPVar (not relevant for this study)

Rotation System 3: 50% annual legume pastures: 50% crops

- 3a – PWPW
- 3b – PWPO
- 3c – PWPB
- 3d – PWPC
- 3e – PvarPVar (not relevant for this study)

Rotation System 4: 50% annual legume pastures: 50% crops (crops follow two consecutive pasture years)

- 4a – PPWW
- 4b – PPOW
- 4c – PPWB
- 4d - PPCW

Rotation System 5: 100% crops

- 5a – WCWL
- 5b - WBCWBL

Management protocols were developed for each crop and pasture to ensure that the leading available information was integrated into the production requirements of each crop over time. As new technology and information were made available, the protocols would be updated. This was most often with regards to cultivars. As mentioned before, a no-tillage management approach was used for the duration of this trial. Standard farm implements were used to plant crops, protect them against pests, disease and weeds, and harvest the crops. The necessary pest, disease and weed controls were implements by field staff in collaboration with the befitting specialist for the specific issue. Each year, the appropriate crop cultivars were planted according to the above-mentioned protocols. The appropriate mixture of medics and clovers were used to plant the pastures which were re-seeded when necessary.

3.5) Financial Information

The yields, quality and all economic data were recorded each year for each individual crop and camp in this trial. This was done using a Microsoft EXCEL version of MICRO-COMBUD that was written specifically to accommodate the experimental design. This programme allowed for easy verification of each data point that was either captured or calculated for any of the treatments. The economic data captured included all direct and indirect allocatable variable input costs per hectare as well as the gross income per hectare (not including marketing costs) for each crop in each rotation system being tested in the trial. Livestock also contributed to gross income during the pasture phase of the rotation through meat and wool sales. The economic data is expressed in a detailed enterprise budget each year from 2002 until 2020. In depth management, yield and input records are also available, detailing the exact management and inputs for each camp. A map showing the camp layout for the trial can be found in Appendix 1.

Gross margin analyses were conducted for each treatment each year from 2002 until 2020 based on the following:

Gross income:

- Calculated as yield per hectare x product price at the date when delivered to the silo (during harvest).
- Price per ton after silo marketing costs.

Directly allocatable variable costs:

- Actual price paid for products and services on the date at which the product or service was supplied to the trial site.

Indirectly allocatable variable costs:

- The cost of repairs and maintenance were based on the “Guide to Machinery Costs” for each specific year during which the machinery and implements were used on the trial site.
- Fuel costs were also based on the “Guide to Machinery Costs” for each specific year during which the machinery and implements were used on the trial site.
- The cost of energy was based on the average (coastal) price per litre of diesel for the period from April to October each year, as supplied by the Automobile Association.

3.6) Wheat & Barley Quality Indicators & Rating Systems

3.6.1) Quality Indicators

Quality impacts the pricing of both wheat and barley, with higher quality grain fetching higher prices and thus impacting the gross income of systems. For this thesis the quality indicators considered were hectolitre mass (HLM) and protein content for wheat and kernel plumpness and nitrogen content for barley. Table 3.1 outlines the HLM and protein content requirements for the different wheat grades. BS (super grade) is the highest rating and FEED is the lowest.

Table 3.1 - The HLM and protein content requirements for the grading of bread wheat as outlined by CapeAgri.

Hectolitre Mass (kg/hl)	Protein Content (%)				
	> or = 12.5	11.5 – 12.4	10.5 – 11.4	9.5 – 10.4	8.5 – 9.4
> or =76.0	BS	B1	B2	B3	CO
74.0 – 75.9	B3	B3	B3	B3	CO
68.0 – 73.9	CO	CO	CO	CO	CO
64.0 – 67.9	FEED	FEED	FEED	FEED	FEED

Note: Only BS, B1, B2, B3 are official bread wheat grades. Class Other (CO) and FEED grades are created by CapeAgri (De Lange, 2019).

Table 3.2 outlines the kernel plumpness and nitrogen content for the different barley grades. There are only two barley grades, namely feed or malt grade. Malt grade has higher quality requirements and fetches a higher price than feed grade. Barley classified as malt grade is used predominantly in the brewing industry whilst barley classified as feed grade is mainly used in the production of animal feed.

Table 3.2 - The barley kernel plumpness and nitrogen content requirements for either malt or feed grade.

Grade	Plumpness (%)	Nitrogen (%)
Feed	<70	<1.5 or >2.0
Malt	>=70	>=1.5 - =<2.0

3.6.2) Rating Systems

To compare wheat and barley quality between systems and sub-systems a rating system was used. This rating system assigned numerical values to each grade, allowing for the comparison of systems and sub-systems. The wheat rating system (Table 3.3) assigned numerical values, starting at 1 for super grade (BS) wheat and ascending to the rating of 6 for feed grade wheat which is considered the lowest quality wheat. Therefore, the higher the rating for each system or sub-system, the lower the wheat quality.

Table 3.3 - Wheat grades and their associated ratings for quality comparison.

Wheat Grade	Rating
BS	1
B1	2
B2	3
B3	4
CO	5
FEED	6

There are only two barley grades, with malt grade consisting of higher quality barley than feed grade. The barley rating system (Table 3.4) assigned malt grade the numerical value of 1 and feed grade the numerical value of 2. Therefore, the lower the rating for each system or sub-system the better the barley quality.

Table 3.4 - Barley grades and their associated ratings for quality comparison.

Barley Grade	**Rating**
Malt	1
Feed	2

Chapter 4 – Yield and Quality Results and Discussion

4.1) Introduction

The data collected from the Tygerhoek experimental trials discussed in Chapter 3 will be split into two fields of results: Chapter 4 which will focus on the yield and quality data from the trial and; Chapter 5 which will look at the economic data (gross margins and input costs) collected from the trial. The data is derived from camps planted to wheat (28 plots), barley (10 plots), canola (8 plots), lupines (4 plots) and oats (6 plots) each year. Chapter 4 will focus on identifying the factors that drive the profitability of crop rotations in the Middle Rûens area.

Climatic conditions, cultivar choice and the location of certain systems within the trial layout all factored into the production levels seen for different crops and systems. For example, camp 11, which was planted to one repetition of sub-system 5a (WCWL), was located on a part of the farm that had self-compacting soil which was a major contributing factor to the lower yields seen in this repetition when compared to the second repetition for sub-system 5a planted in camp 18. The self-compacting soil in camp 11 also contributed to weed control problems. Weeds were harder to control as they did not grow actively, resulting in stronger competition between the weeds and the crops, lowering crop yields.

Chapter 4 starts with a discussion of the overall average annual yields and growing season rainfall. This will be followed by the annual yields of wheat in different systems and then wheat in different sub-systems both annually and over the entire 19-year period in total. The yields of wheat in different three- and four-year crop sequences will also be reviewed. Yield quality will be analysed in terms of HLM (hectolitre mass) and protein content and a rating system (as mentioned in Chapter 3) is also used to compare the quality of wheat from different systems and sub-systems. The same breakdown of analyses used for wheat will also be used when reviewing barley yields and quality, but only the yields of the three-year crop sequences will be considered instead of both three- and four-year sequences. Barley quality will be reviewed in terms of plumpness and nitrogen content and a rating system similar to that used for wheat will also be used for comparison purposes. For canola, the yields over time and between sub-systems will be dealt with as well as the canola yields from different four-year crop sequences. Table 4.1 below shows the crop rotation systems and sub-systems at Tygerhoek. These systems are shown again to ease the reading of Chapter 4.

Table 4.1 - Crop rotation systems and sub-systems at Tygerhoek Experimental farm.

System	Sub-Systems
System 2 (67% annual legume pastures: 33% crops)	• 2a – PPW • 2b – PPO

	• 2c – PPB
System 3 (50% annual legume pastures; 50% crops)	○ 3a – PWPW ○ 3b – PWPO ○ 3c – PWPB ○ 3d - PWPC
System 4 (50% annual legume pastures; 50% crops)	▪ 4a – PPWW ▪ 4b – PPOW ▪ 4c – PPWB ▪ 4d – PPCW
System 5 (100% crops)	◘ 5a – WCWL ◘ 5b - WBCWBL

4.2) Annual Yields & Growing Season Rainfall

The trial site, Tygerhoek Experimental Farm, is situated in the Overberg region of South Africa which is known as a winter rainfall area but can receive up to 55% of its rainfall during the summer months (Hardy, 2007). The growing season for crops planted in this area is usually April to September and this is when frequent rainfall is needed for good plant growth and higher yields. Over the 19-year trial period (Figure 4.1), the average total rainfall was 488 mm and the average growing season (April to September) rainfall was 243 mm, which shows that close to 50% of the total average rainfall fell during the growing season, whilst the other 50% fell during the other months of the year. The exact monthly rainfall measurements for each year can be found in Appendix 3. Climatic conditions such as rainfall are known to be the predominant factor in the determination of crop yields, especially in a rain-fed production system. The dispersion, amount and timing of rainfall is paramount in determining the crop yields during a production season.

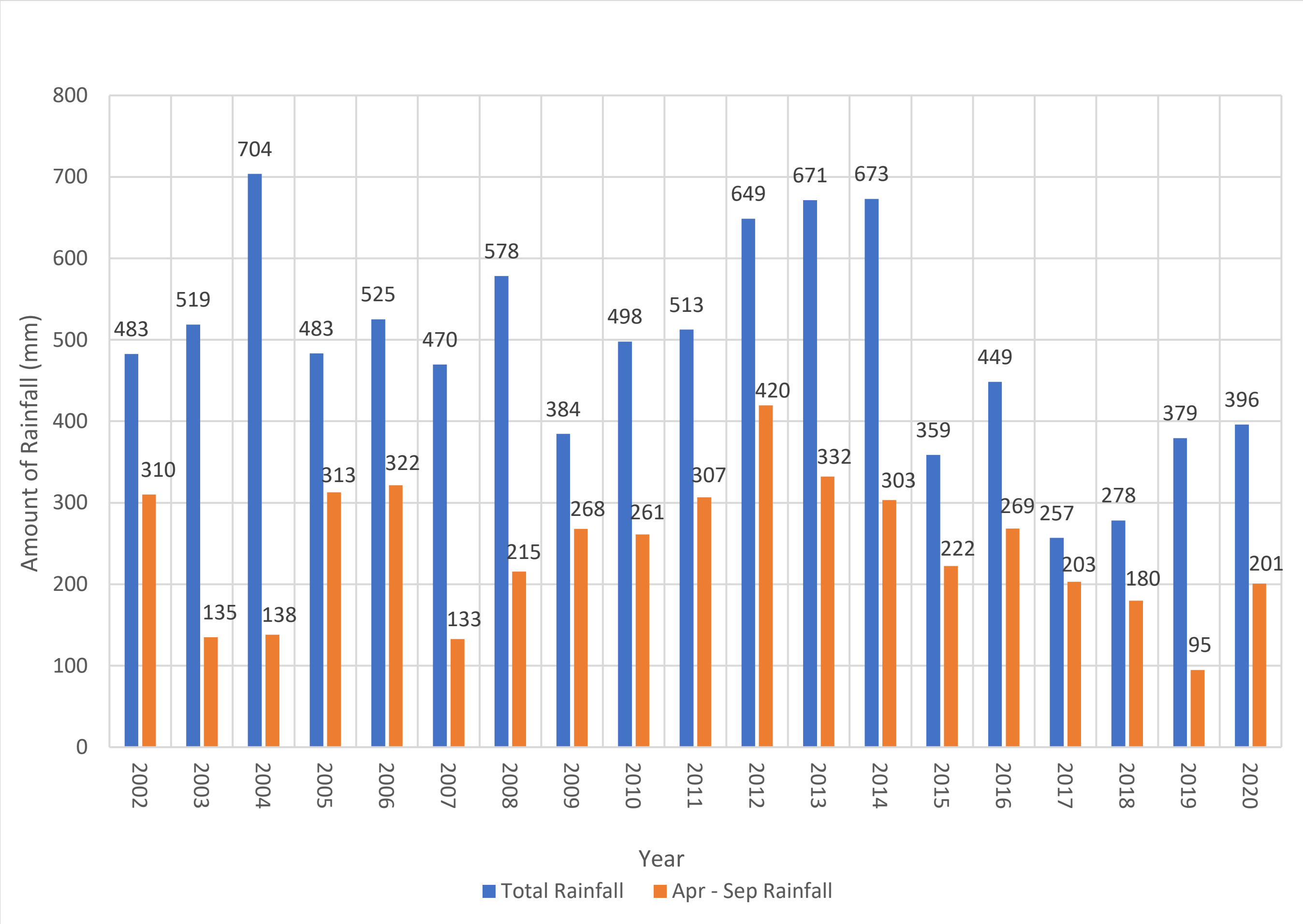


Figure 4.1 - Total annual rainfall and growing season (April to September) rainfall at Tygerhoek Experimental Farm from 2002 – 2020.

The average annual yields of wheat, barley and canola as well as the growing season rainfall is illustrated in Figure 4.2 below. Canola has consistently lower yields than both wheat and barley but followed similar yearly trends to both crops. Wheat and barley yields were similar from 2002 – 2005, in 2006 the average wheat yield was much higher than the average barley yield, after which the yields became similar again from 2007 – 2015. From 2016 – 2020 barley yields were higher than those of wheat. Wheat, barley and canola yields were highest in 2020 and all three crops had their lowest yields in 2019.

Crop yield trends seemed to generally follow growing season rainfall trends - when growing season rainfall was low, yields declined in most cases, but this was not always the case. It is dependent on the dispersion of the rainfall during the growing season, not only the amount of rainfall. For example, in 2020 yields reached an all-time high, even though the amount of growing season rainfall was only an average amount, but the rain fell consistently throughout the growing season. This allowed the crops to flourish and produce the record high yields shown. This shows the considerable effect of rainfall dispersion/timing on crop yields. Another example of this was in 2004, when the total rainfall for the year was 704 mm but the growing season rainfall was only 138 mm, resulting in some of the lowest crop yields seen throughout the trial period.

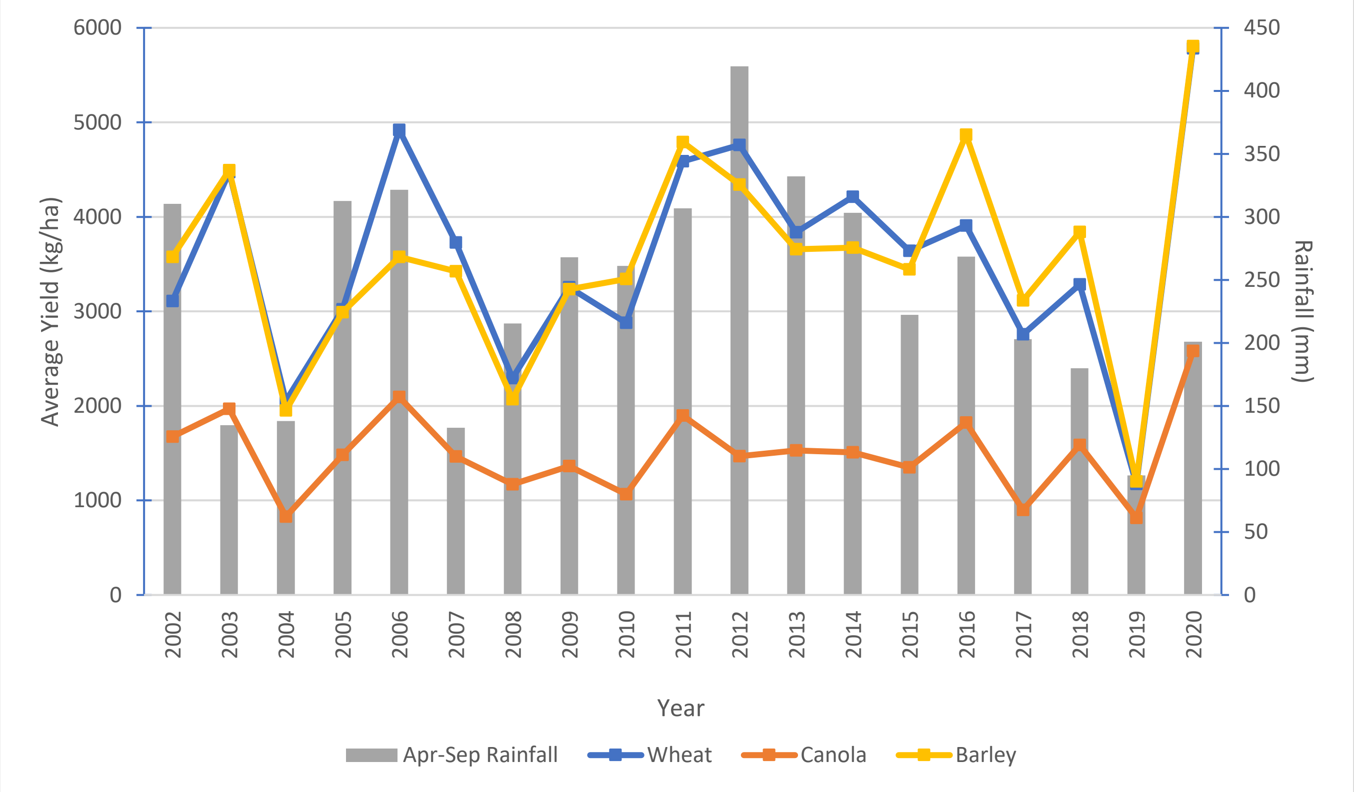


Figure 4.2 - The total average annual wheat, canola and barley yields and growing season rainfall (Apr-Sep) from 2002-2020.

Rainfall is predicted to become more erratic in future years, due to climate change (Daniel, 2015) which could potentially have a devastating effect on crop yields. Practices associated with CA, such as permanent organic soil cover, can reduce the impacts of climate change and increase the resiliency of cropping systems (Panagopoulos *et al.*, 2014; Basche *et al.*, 2016) . The quick recovery of crop yields in 2020 after the drought in 2019 can be attributed to the increased drought resiliency of the cropping systems after many years under CA management.

4.3) Wheat Yields & Quality

4.3.1) Wheat Yields

The average annual wheat yields varied between around 1 000 kg/ha and close to 6 000 kg/ha over the 19-year trial period (Figure 4.3). The highest average annual wheat yield was 5 791 kg/ha in 2020, the lowest average yield was 1 160 kg/ha in 2019. The years with the best average wheat yields were 2003, 2006, 2012 and 2020. This can mainly be attributed to higher growing season rainfall. The years with the lowest average wheat yields were 2004, 2008 and 2019. The yields in

2019 showed the lowest standard deviation, meaning this was the year with the least variability in the data (yields were all close to the mean), whilst 2012 had the highest standard deviation, showing the most variability in the data. The spread of the data remained similar throughout the trial, except for the period between 2011 and 2014, where there was a more prominent difference between the minimum and maximum wheat yields. From 2016 onwards there was very minimal spread in the data.

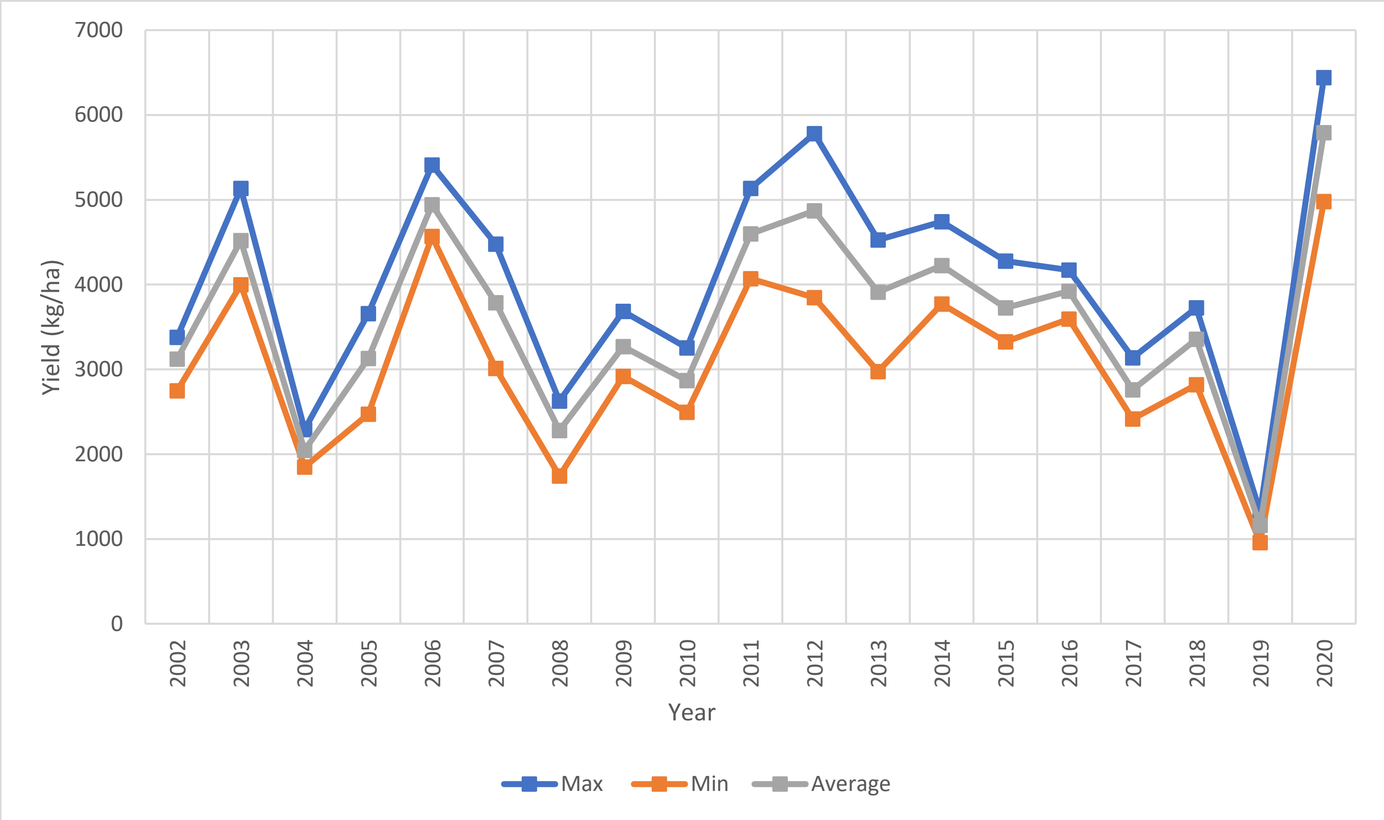


Figure 4.3 - The maximum, minimum and average annual wheat yield from 2002-2020.

4.3.1.1) Wheat over time (per system)

In Figure 4.4, the annual wheat yields of the four main systems are shown. This was done to show the general trends between the systems over time. A graph depicting each wheat sub-system over time would be too complex as wheat was a component of most sub-systems in the trial. The average wheat yields for different systems were similar most years, but the average yield for system 5 was considerably lower than the yields of the other three systems in 2012, 2013 and 2015. Over the 19-year period (2002 – 2020), system 3 had the highest average wheat yield overall, followed by system 4 and system 2. System 5 had the lowest overall average wheat yield.

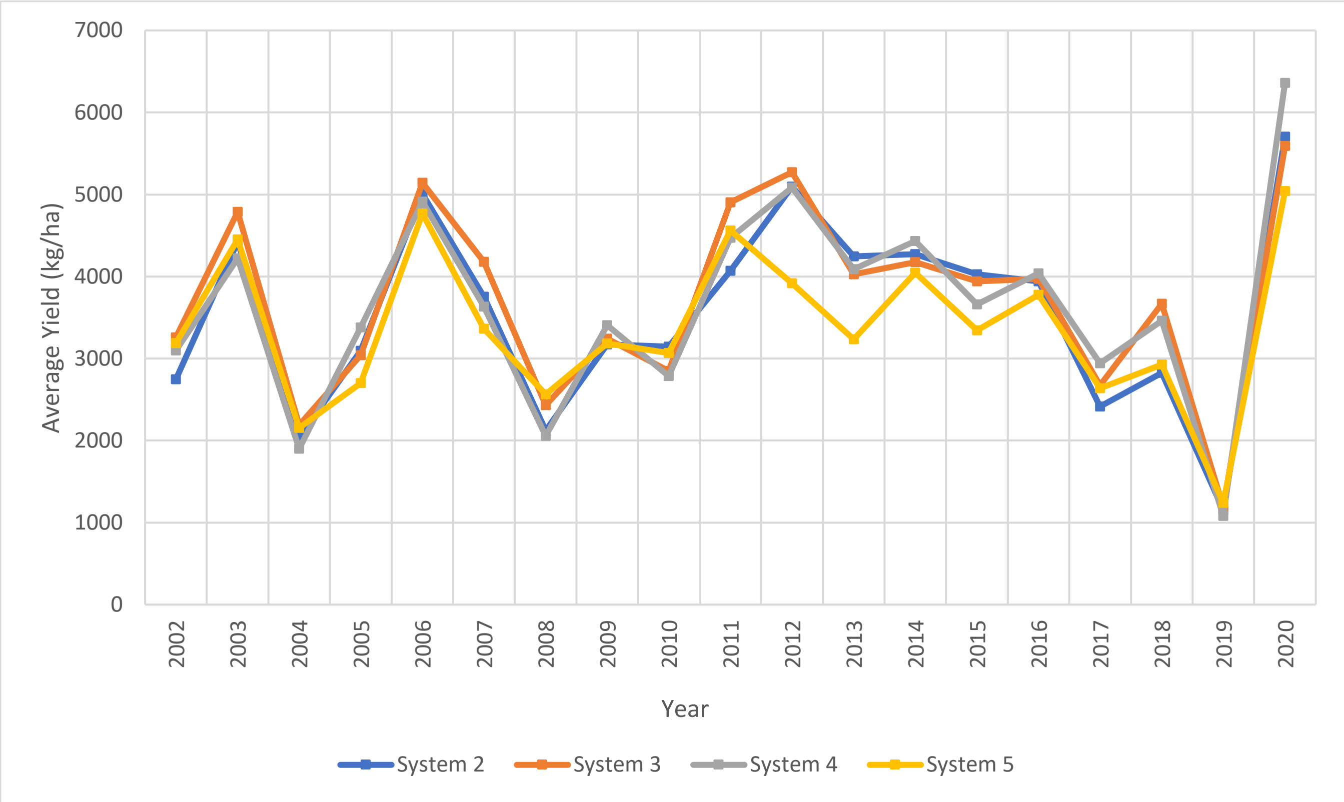


Figure 4.4 - The average wheat yields for different systems from 2002-2020.

4.3.1.2) Wheat Yields per sub-system

The average wheat yields per sub-system over the 19-year trial period are illustrated in Figure 4.5. The average wheat yields for the different sub-systems ranged between 3 250 kg/ha and 3 831 kg/ha. The overall average wheat yield over the 19 years was 3593 kg/ha (shown as the orange horizontal line in Figure 4.5). Sub-systems 3b (PWPO), 3d (PWPC), 4b (PPOW), 4c (PPWB) and 4d (PPCW) all had above average wheat yields, whilst all other sub-systems had below average wheat yields. This shows that system 3 and 4 had higher wheat yields on average, than systems 2 and 5.

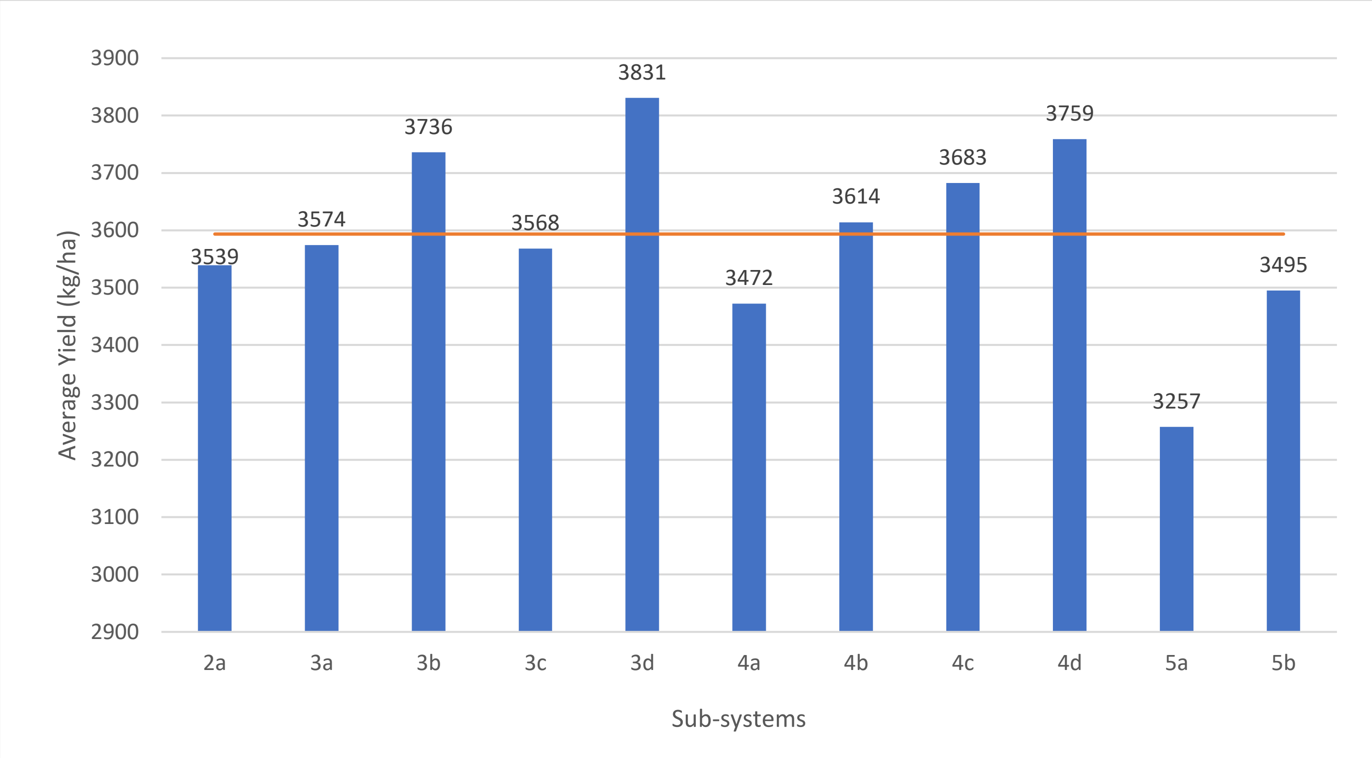


Figure 4.5 - The average wheat yield per sub-system over a 19-year period from 2002-2020. The line depicts an overall average cost of all sub-systems tested.

Sub-system 3d (PWPC) showed the highest average wheat yield over the 19 years, closely followed by sub-systems 4d (PPCW) and 3b (PWPO). All three of these sub-systems included two years of pastures, either consecutively (PPCW) or staggered between crops (PWPC, PWPO). The annual legume pastures assist in nitrogen fixation in the soil (Giller *et al.*, 2009), providing additional nitrogen to the subsequent crops, which promotes higher yields. It also plays a role in grass weed management, resulting in lower weed pressure in the cash crop year.

The lowest average wheat yield was seen in sub-system 5a (WCWL), followed by 4a (PPWW) and 5b (WBCWBL). One repetition of sub-system 5a was planted in camp 11, which as mentioned previously, had self-compacting soil and weed problems which lowered the crop yields for 5a. This is illustrated in Figure 4.6, which clearly shows how average wheat yields from camp 18 were almost always higher than those from camp 11, both of which were part of the same sub-system (5a).

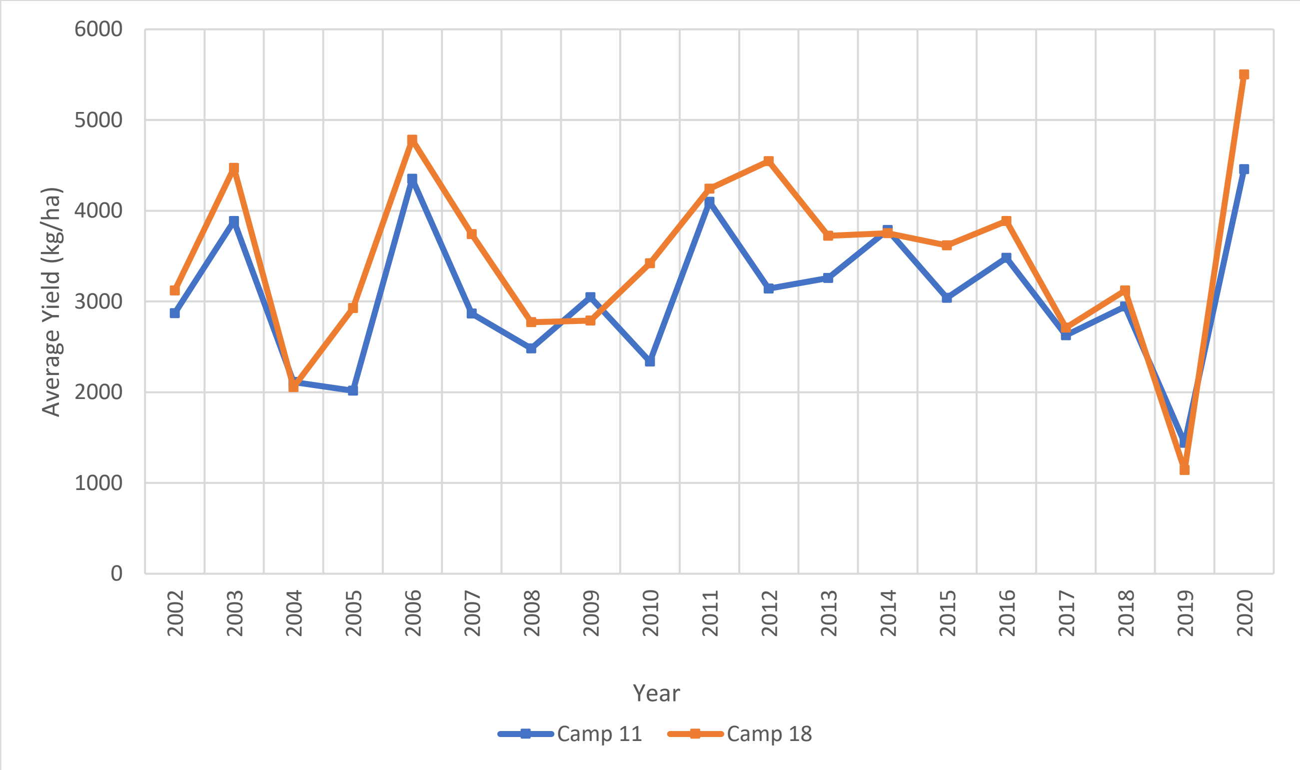


Figure 4.6 - A comparison of annual wheat yields from camps 11 and 18, both of which are part of sub-system 5a (WCWL).

In sub-system 5b, wheat always followed barley, both of which belong to the same family Poaceae, limiting the types of herbicides that can be used (Giraldo *et al.*, 2019). This made weed control difficult as there is no "break year" where grass weeds can be controlled, therefore more weeds were prevalent in the wheat and barley from sub-system 5b. These weeds competed with the crops and lowered yields. Sub-system 4a included two years of wheat monoculture (WW) which also caused weed control issues and disease build-up which lowered yields.

4.3.1.3) Yields for Different Three-Year Wheat Sequences

The average yields of wheat from different three-year crop sequences were considered in order to highlight the role of crop sequences in systems research (Figure 4.7). On average, wheat yields of crop sequences containing pastures were higher than those not containing pastures. This could be due to the nitrogen-fixing abilities of the legume pastures as well as the reduced weed prevalence in wheat following pastures. Pasture years were used as "break" years for weed control which reduced weed pressure in the subsequent crop years. The crop sequence canola-pastures-wheat (CPW) had the highest overall average wheat yield, followed by the crop sequence pastures-canola-wheat (PCW). Both these sequences contained canola and pastures in the two years before wheat, which allowed for nitrogen fixation and weed control. Canola belongs to the Brassicaceae family ("History of Canola Seed Development", 2021) which allowed herbicides targeting grass weeds to be sprayed, reducing the grass weed prevalence in subsequent wheat and barley years. Crop sequence oats-pastures-wheat (OPW) had the third highest average wheat yield. During the early years of the trial oats were used for haymaking, which allowed for a more rigorous weed control regime to be used in camps where oats were planted. The more stringent weed control kept the weed seedbank at bay, reducing the number of weeds found in wheat planted after oats which resulted in higher yields of wheat.

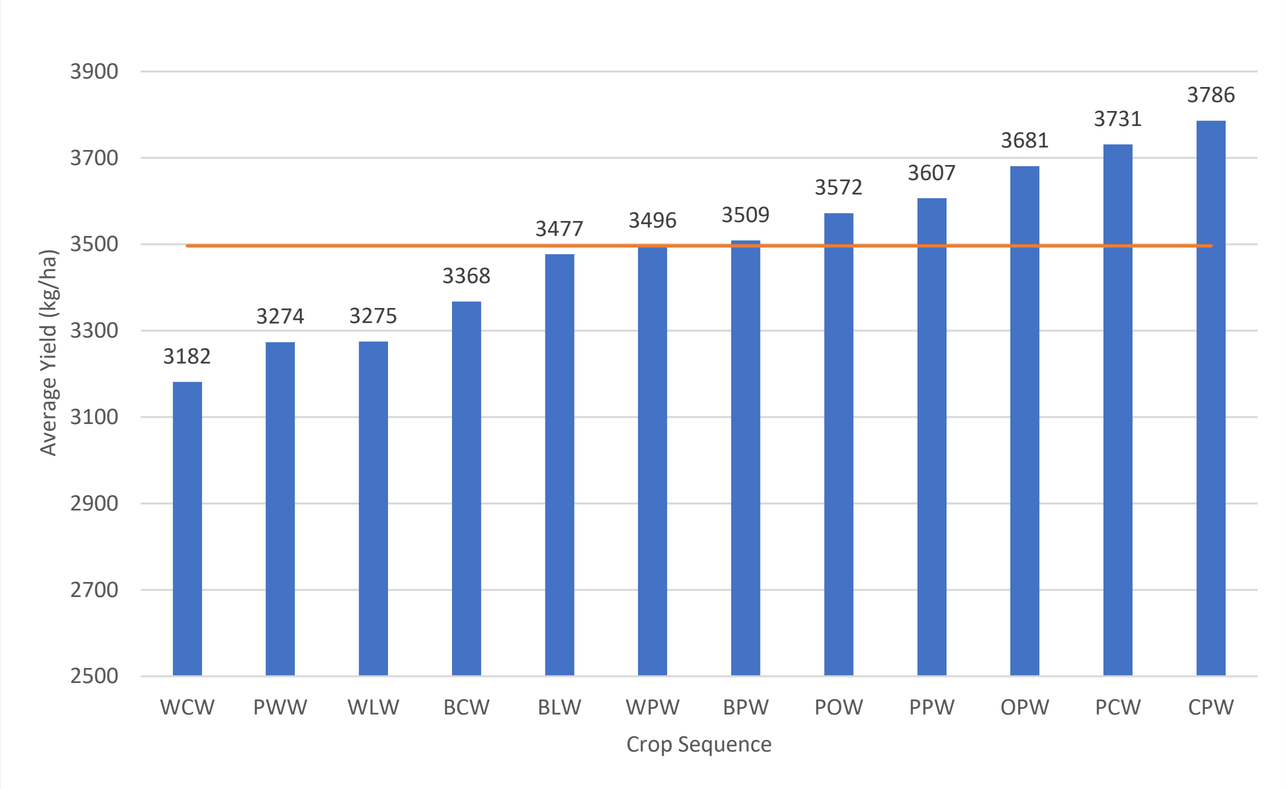


Figure 4.7 - The average wheat yields of different three-year crop sequences over a period of 17-years from 2004-2020.

The only crop sequence that contained a pasture year, but had a low average wheat yield was PWW, where wheat followed wheat. The first year of wheat following pastures would still be benefitting from the increased nitrogen levels and lower weed densities seen after a pasture year. However, the second year of wheat will follow on from wheat and low nitrogen levels, weed and disease problems could cause lower wheat yields after this sequence. The other crop sequences containing two wheat years were also seen to generally have lower average wheat yields. Crop sequence WCW had the lowest average wheat yield over the trial period, followed by PWW and WLW. Crop sequence WCW would have been part of sub-system 5a (WCWL) which had one repetition planted in camp 11, which is known for having lower yields due to the unfavourable soil-type in the camp. Crop sequence WLW was from sub-system 5b (WBCWBL), one of the continuous cash cropping systems which were often found to have lower yields due to the lack of rigorous weed and disease control opportunities as there was no pasture “break” years between the cash crops.

4.3.1.4) Yields for Different Four-Year Wheat Sequences

The crop sequence pasture-canola-pasture-wheat (PCPW) achieved the highest overall average wheat yield (3 891kg/ha) (Figure 4.8). This sequence contained the three-year PCW crop sequence which also had the highest average wheat yield for the three-year crop sequences. The top eight crop sequences all included two pasture years, some consecutively and others staggered. The only four-year sequence that contained pastures but had a low overall average wheat yield was PPWW, but in this sequence wheat followed wheat, which might have been the reason for the low average yield. This shows the highly beneficial effect of including pastures into a cropping system.

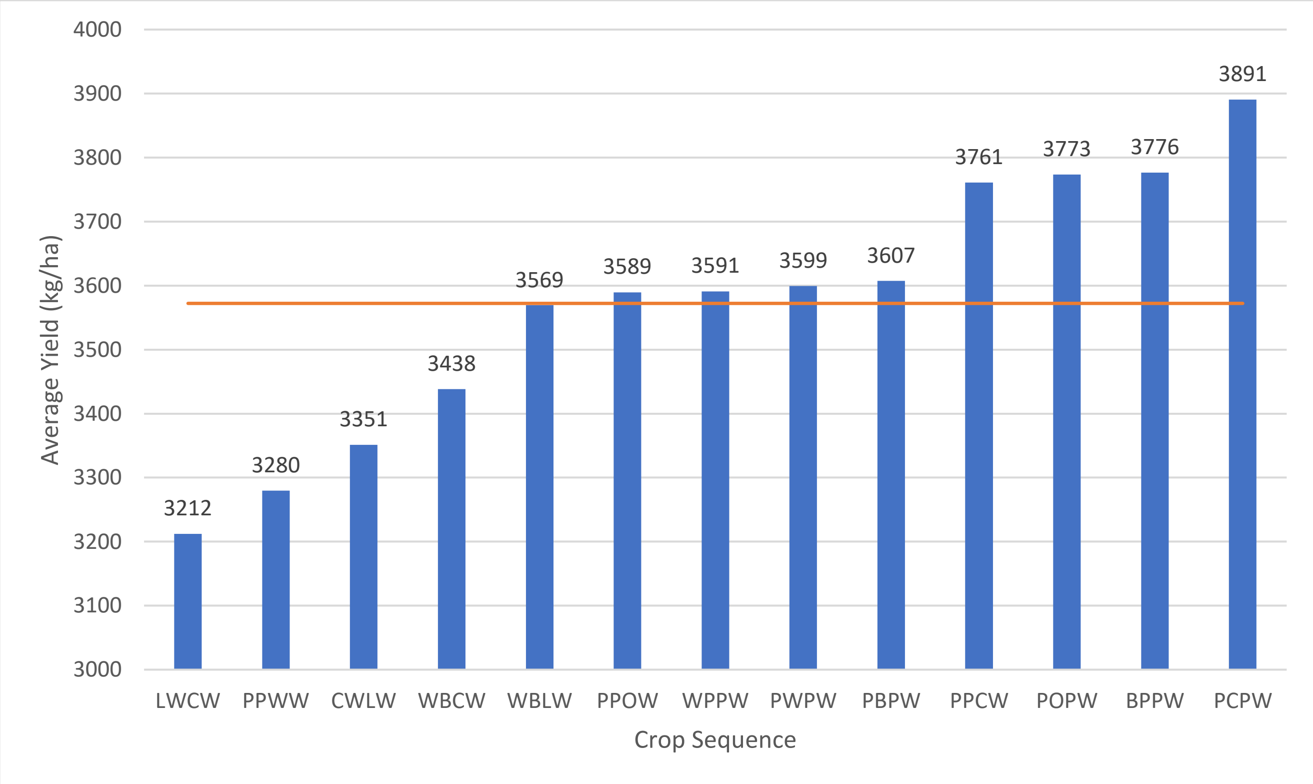


Figure 4.8 - The average yield of wheat in different four-year crop sequences over a 19-year period from 2002-2020.

The crop sequence LWCW had the lowest overall average wheat yield (3 212 kg/ha) and this sequence also contained the three-year sequence WCW which also had the lowest average wheat yield in the three-year sequences. Both LWCW and CWLW (third lowest wheat yield) came from sub-system 5a, which included a repetition planted in camp 11, contributing to the low yields. Lupine is often used in crop rotations for its nitrogen-fixing capabilities and provides a useful break in the build-up of diseases in many cereal crops (Engelbrecht, 2016). Lupine usually contributes to higher yields in subsequent grain crops, but this was not seen to be the case in this trial (Figure 4.8). This might have been due to the limited lupine cultivar choice in South Africa which prevents farmers from being able to access premium lupine cultivars.

4.3.2) Wheat Quality

The grain quality of wheat is dependent on a few different factors, but the quality requirements change according to what the grain will be used for. The grain quality is determined by physically grading it, both visually and with the use of instruments. Through this process, the grain's suitability for its intended purpose and its grade are determined, this being directly linked to the value of the grain. The grading of the grain is a guideline by which the buyer can decide whether the grain can be used for his/her specific purposes and what he/she can pay for it (Lusse, 2016). Grain quality is largely dependent on factors such as the type of grain, genetics, cultivation practice and the handling and storage of the grain. The following properties are usually used to determine grain quality, these are: moisture content, hectolitre mass (HLM), foreign matter, percentage of coloured, broken and damaged grains, milling quality, protein and oil content, vigour, mycotoxins and the presence of insects and fungi (Lusse, 2016). For this thesis, the HLM and protein content were considered when determining wheat quality and grading as these are the two main grading requirements for wheat in South Africa. The exact HLM and protein content parameters for each wheat grade are outlined in Chapter 3.6.

4.3.2.1) Hectolitre Mass (HLM)

HLM is the volumetric mass of wheat and is the easiest, most common way of quantifying wheat. It is a measure of the grain mass density and is expressed as mass per volume. HLM is used as a means of determining wheat quality as it provides an estimation of flour yields. The factors which affect the HLM value are grain density, grain size and shape, wheat maturity, cultivar type and diseases. HLM can be influenced by climatic conditions during the growing phase and during the harvest period; as well as by frost damage and foreign matter in the grain (Lusse, 2016). The HLM requirements for the different wheat grades have been outlined previously in Chapter 3.6.

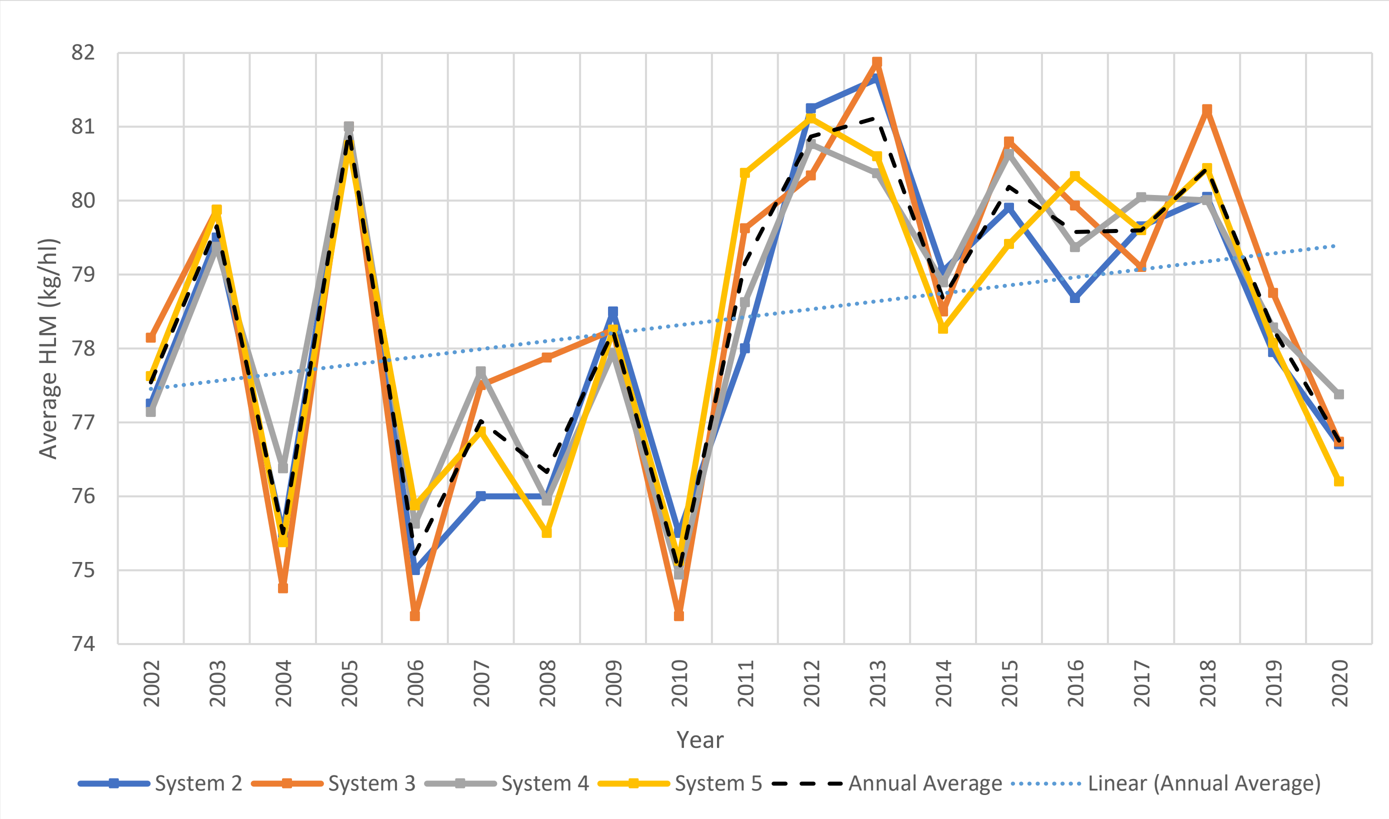


Figure 4.9 - The average HLM of wheat in different systems from 2002-2020.

The overall average HLM of wheat planted during the trial period, increased over time from around 77.5 kg/hl in 2002 to around 79.5 kg/hl in 2020, as shown in Figure 4.*9*. For wheat to be graded as BS (super grade), the highest grade, the HLM will need to be above or equal to 76 kg/hl and the kernel protein above 12.5%. If the HLM is above 74 kg/hl and the kernel protein is above 10.5% it is still classified as good enough for the milling industry. Each grade step-down comes with a lower associated price.

The average HLM for all systems dropped in 2004, 2006 and 2010 but rose steadily after 2010 and stayed relatively high until 2018, after which it decreased again but still not to the levels it was at during the early years of the trial. All three years with the lowest average HLM (2004, 2006 and 2010) were dry years. Drought is known to cause a decrease in the HLM of wheat and an increase in the protein content, as the HLM and protein content of wheat are inversely proportional quantities (Nortje, 2020).

The average HLM of wheat in most systems peaked in 2005, 2012 and 2013. This could be attributed to good growing season rainfall during these years, which increased the HLM of the wheat. The HLM of system 3 was often below average and was more varied than other systems. System 3 was the only system to drop below 74 kg/hl, meaning the average wheat in that system from those years would be graded as Class Other (CO) - the lowest grade - purely due to its HLM regardless of protein content.

4.3.2.2) Protein Content

The protein content of wheat has a large effect on the end-use quality of the wheat (Sharma *et al.*, 2020) and can affect the functionality of the wheat. For wheat to be graded as BS, the protein content needs to be above or equal to 12.5% in conjunction with an HLM that is above or equal to 76 kg/hl. However, if the protein content is above 9.5% and the HLM is above 74 kg/hl, the wheat will still be considered to have met the requirements for bread wheat. Protein content is generally known to increase in drier years. Although this may be considered a good thing, the HLM usually decreases in drier years which brings down the grading of the wheat.

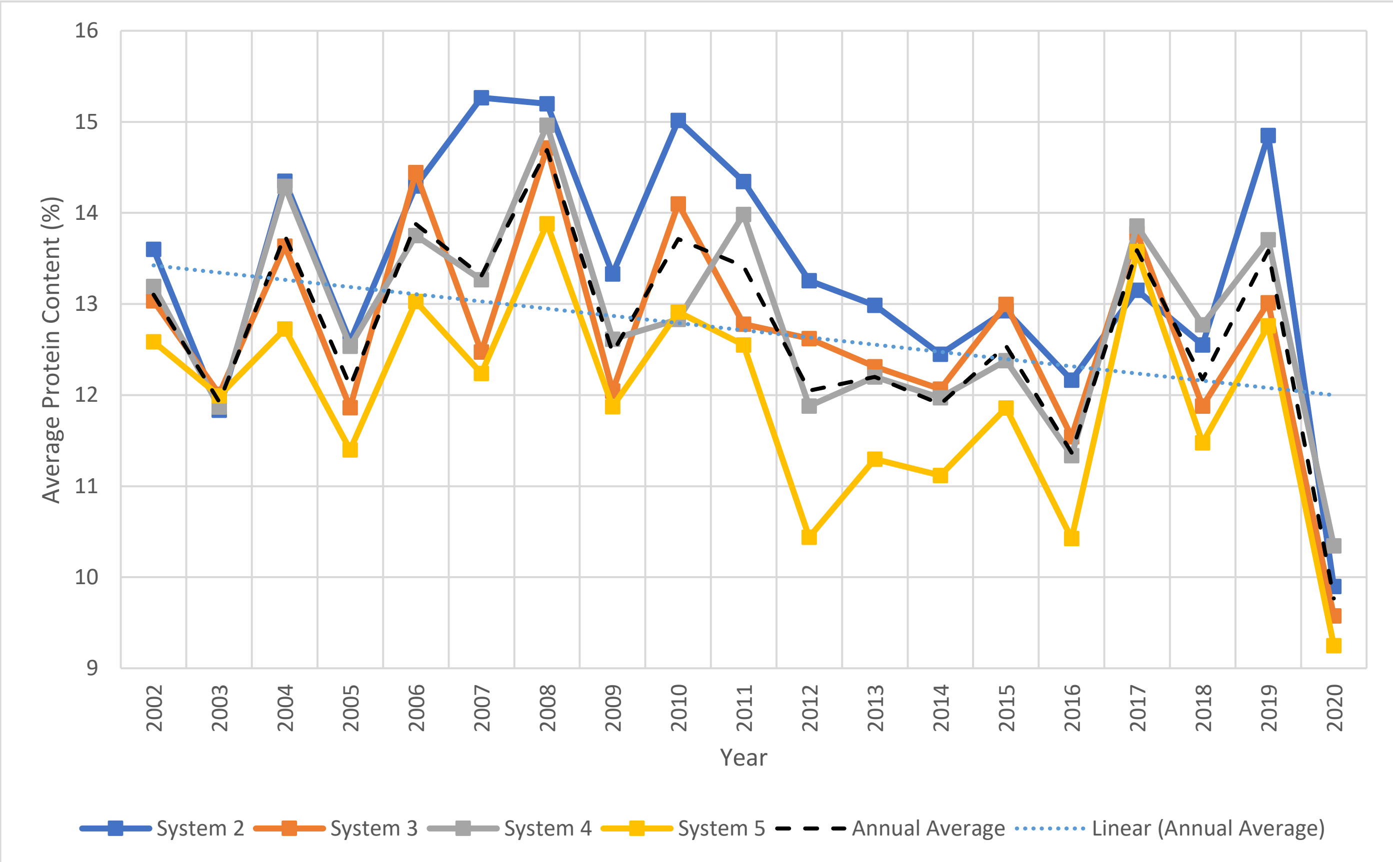


Figure 4.10 - The average annual protein content of wheat in different systems from 2002-2020.

The overall average protein content of wheat was seen to decrease over the trial period, from around 13.5% in 2002 to just above 12% in 2020 (Figure 4.10). Regardless of this decrease over time, the overall average protein remained high enough to be graded well. The overall decrease in protein content could be attributed to the more drought tolerant conditions created under CA principles. Even though there were still drought years (e.g. 2019) the systems were more resilient to this and the protein content didn't spike as high as it did during the earlier years of the trial. System 5 had a consistently lower than average wheat protein content throughout the trial period whilst system 2 had a consistently higher than average protein content throughout the same period.

4.3.2.3) HLM & Protein Content Over Time

The overall average HLM and protein content of wheat from different systems over the 19-year trial period is illustrated in Figure 4.11. For both HLM and protein content, higher values are better. In order to be graded as BS, the protein content should be above or equal to 12.5% and the HLM should be above or equal to 76 kg/hl (De Lange, 2019). As shown below, wheat from systems 2, 3 and 4 were graded as BS (super grade) on average, whilst wheat from system 5 was graded as B1 which is the second-best grade possible, following BS. The protein content of wheat was highest for wheat from system 2, but this system also had the lowest HLM. System 3 had the highest HLM for wheat and the third highest protein content, whilst wheat from system 5 had the lowest protein content and third lowest HLM. All systems had an average HLM above 76 kg/hl, meaning they would qualify for BS grading in terms of HLM but the protein content of system 5 was too low to meet the requirements, causing it to be graded as B1.

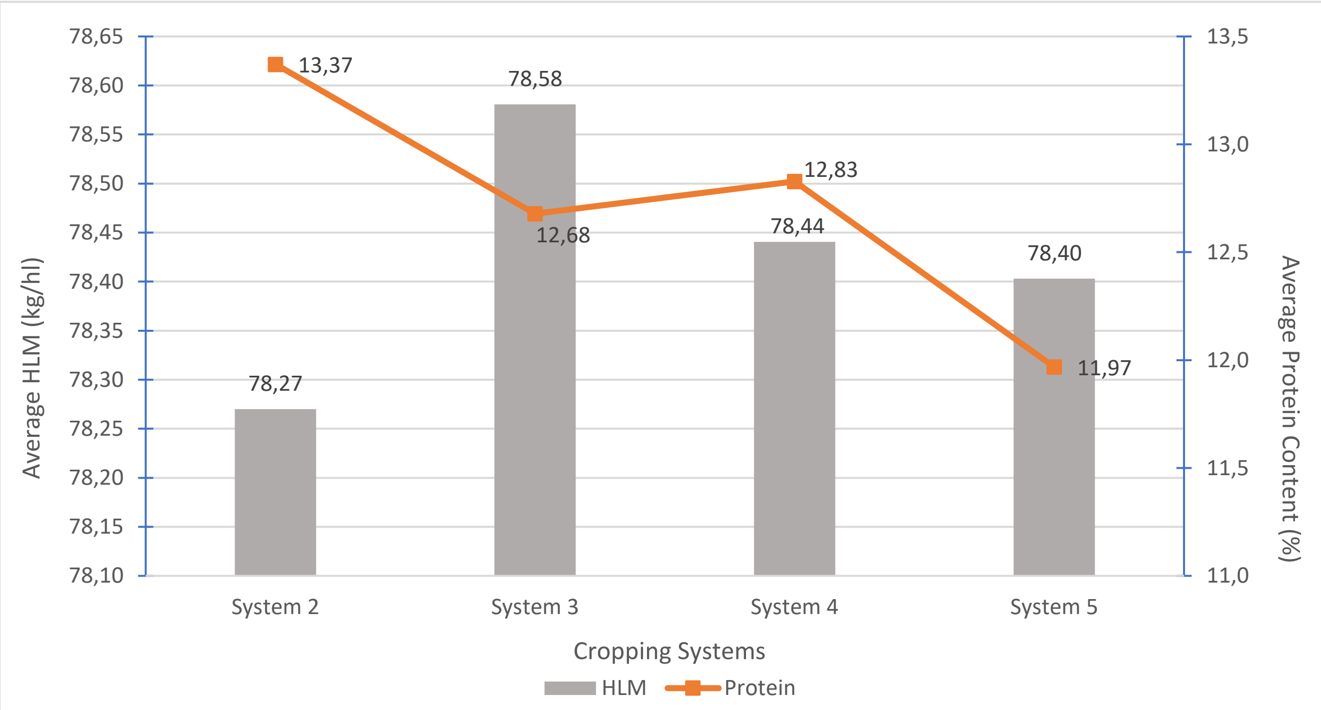


Figure 4.11 - The average HLM and protein content of wheat from different systems over a 19-year period.

Figure 4.12 illustrates the overall average HLM and protein content of wheat in different sub-systems over the entire 19-year trial period. As mentioned before, to be graded as BS the protein content should be above or equal to 12.5% and the HLM should be above or equal to 76 kg/hl. Therefore, wheat from all the sub-systems, except sub-systems 5a (WCWL) and 5b (WBCWBL), could be graded as BS. Wheat from both sub-system 5a (WCWL) and 5b (WBCWBL) would be graded as B1 as the protein content requirements needed for BS were not met. Wheat in sub-system 4d (PPCW) had the highest HLM (78.7 kg/hl) whilst wheat from sub-system 4b (PPOW) had the lowest HLM (78.1 kg/hl), however both were over the 76 kg/hl required to be classed as BS. Wheat from sub-system 2a (PPW) had the highest protein content (13.4%) whilst wheat from sub-system 5b (WBCWBL) had the lowest protein content (11.9%). This caused wheat from sub-system 5b to not be graded as BS, but rather as B1.

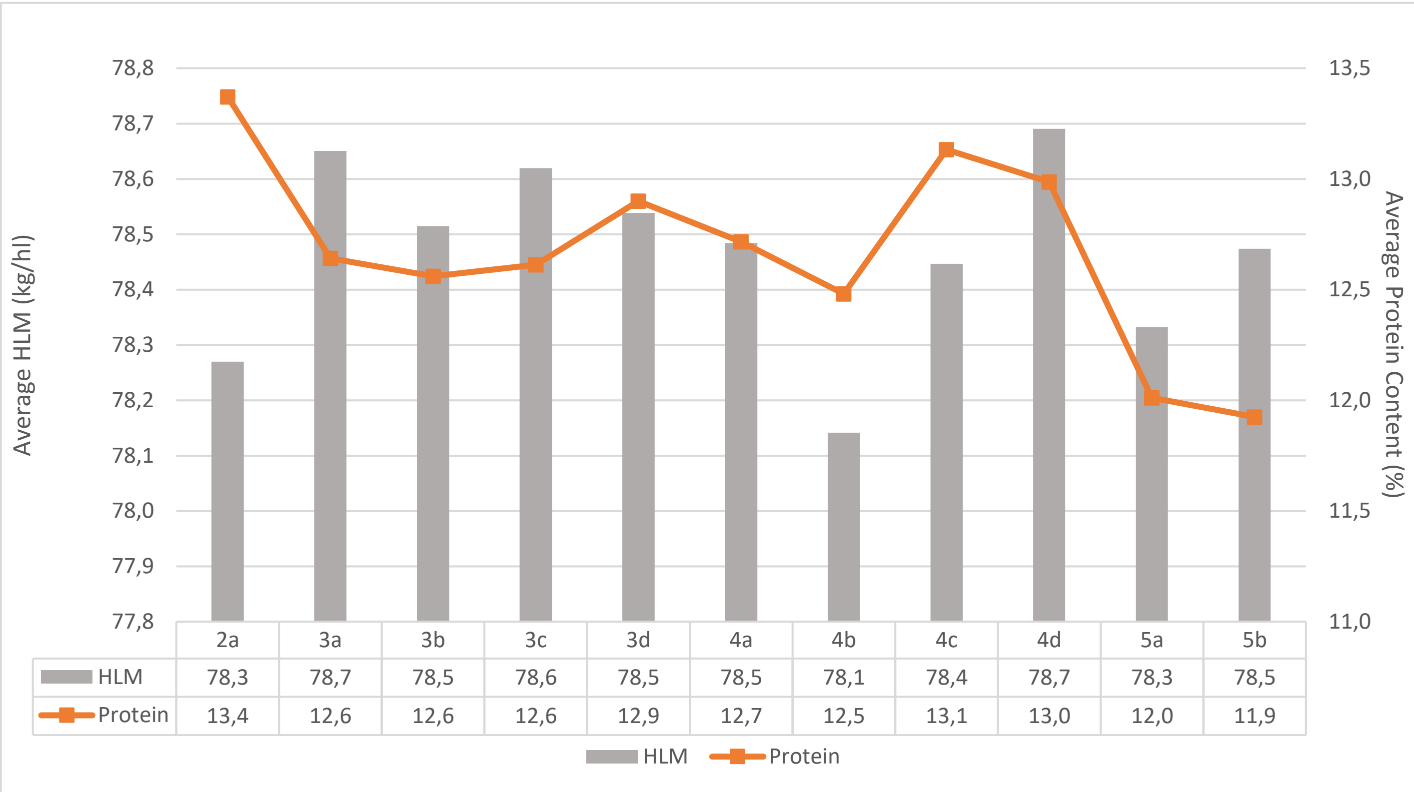


Figure 4.12 - The average HLM and protein content of wheat from different sub-systems over a 19-year period from 2002-2020.

4.3.2.4) Ratings

Ratings were assigned to the respective wheat grades in order to compare wheat quality between systems and sub-systems. A table with these ratings can be found in Chapter 3.6.

The lower the rating the better the wheat grade. As can be seen in the Figure 4.13, wheat from systems 2 and 4 had the lowest overall ratings which were between 2 and 3. This meant that wheat from these systems were graded between B1 and B2 on average. Wheat from system 3 also had a rating between 2 and 3 but slightly more towards 3, which meant that wheat from system 3 will be graded between B1 and B2 on average, but more often as B2. Wheat from system 5 had the highest average rating, which meant it was usually the lowest quality wheat from the four systems being compared. The average rating of wheat from system 5 was just above 3, which meant that wheat from this system would be graded between B2 and B3 on average.

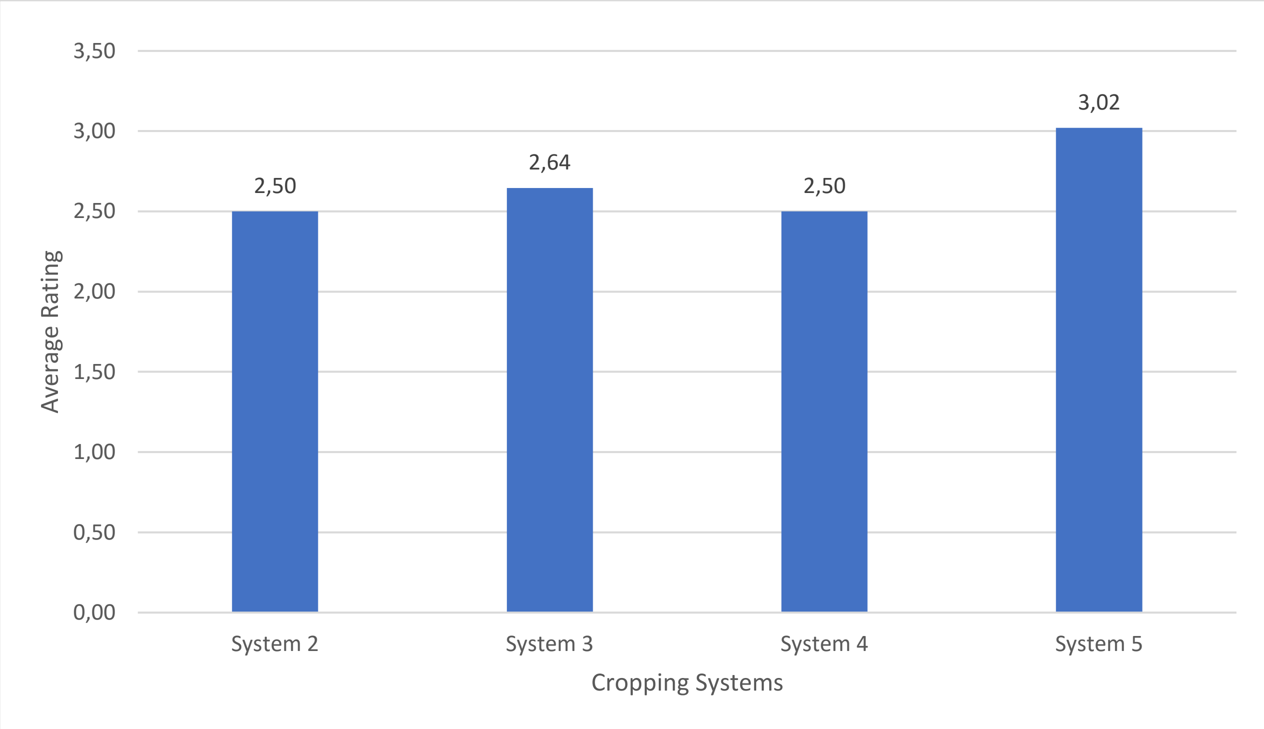


Figure 4.13 - The average ratings of wheat grades from different cropping systems over a 19-year period from 2002-2020.

As mentioned previously, the lower the rating the better the quality/grading. Wheat from sub-systems 4c (PPWB) and 4d (PPCW) had the lowest average ratings, both below 2.5, which meant that wheat from these systems was usually graded between B1 and B2 but more often as B1 (Figure 4.14). Wheat from sub-systems 5a (WCWL) and 5b (WBCWBL) had the highest average ratings, 3.0 and 3.04 respectively. This meant that wheat from sub-systems 5a (WCWL) and 5b (WBCWBL) was graded as B2 on average. This can be attributed to reasons mentioned previously such as the poor soil quality and other issues in camp 11.

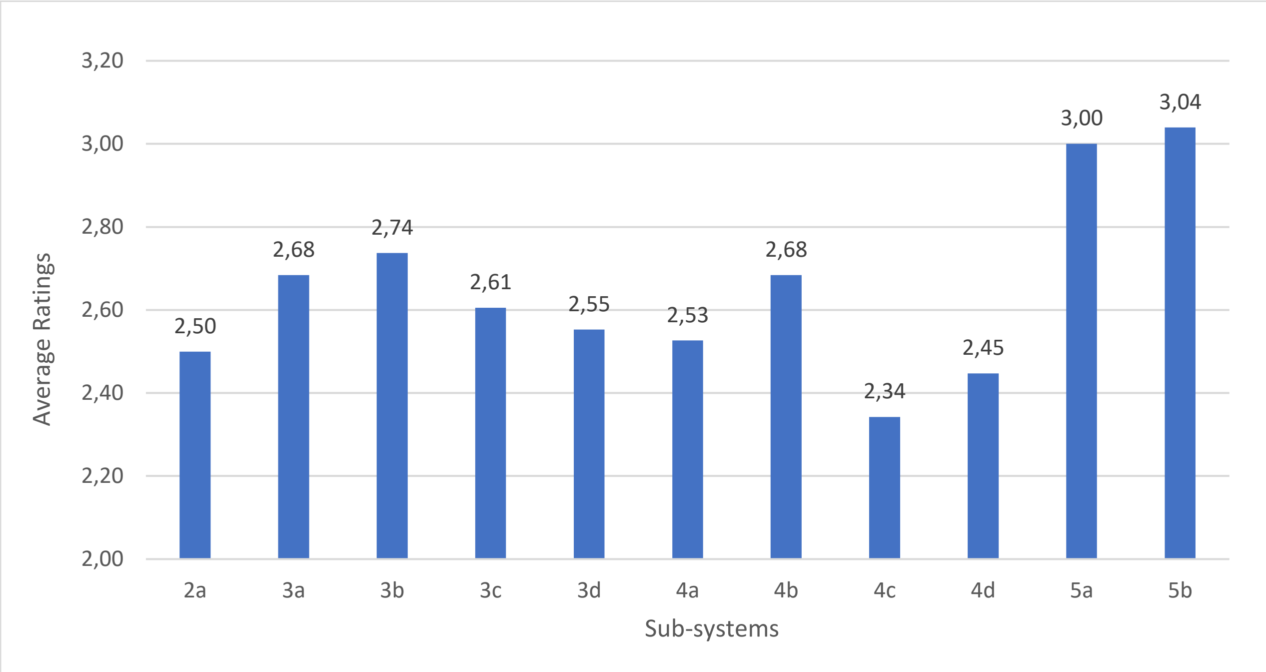


Figure 4.14 - The average ratings of wheat from different sub-systems over a 19-year period from 2002-2020.

4.4) Barley Yields & Quality

4.4.1) Barley Yields

4.4.1.1) Barley Yields over time

As can be seen in Figure 4.15, the overall average barley yields increased steadily over the trial period, from just above 3 000 kg/ha in 2002 to around 4 000 kg/ha in 2020. The highest annual barley yields were in 2020 and 2013, since both years received good, well dispersed growing season rainfall. The lowest annual barley yields were in 2019 (725 kg/ha) and 2008 (1 423 kg/ha), both years had a low amount of growing season rainfall and were following previous dry years. The year with the highest standard deviation for the annual barley yield was 2013, showing that this was the year with the most variability in the data. The lowest standard deviation was seen in 2006, showing that 2006 had the least variable data. More variability in the data was seen from 2008 until 2016, after which the variability decreased and stayed low until the end of the trial period.

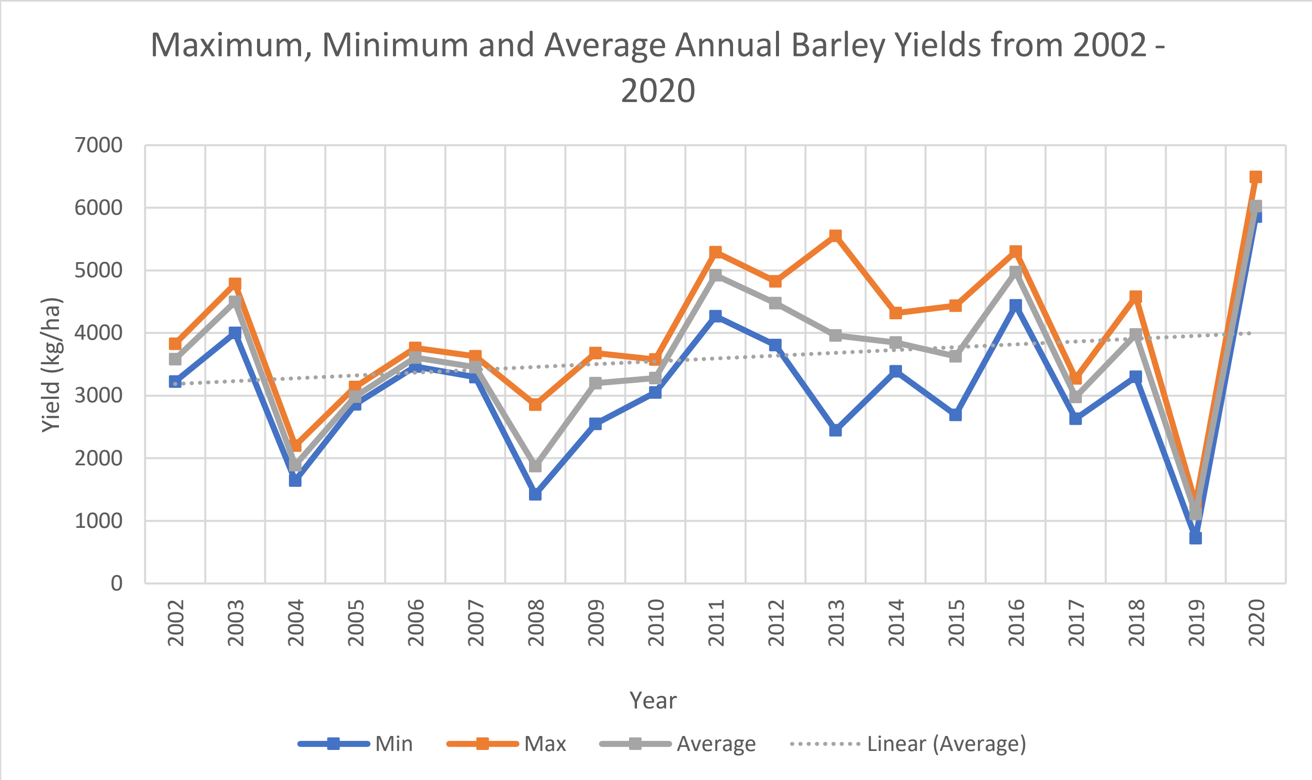


Figure 4.15 - The maximum, minimum and average annual barley yields from 2002-2020.

4.4.1.2) Barley Yields according to Sub-Systems

The average annual barley yields of each individual sub-system were able to be shown over time, unlike those of wheat, as there are only four sub-systems containing barley – one from each system - allowing for a much clearer graph (Figure 4.16).

The barley yields for all sub-systems were similar until 2007, after which they differed from each other until 2017, and then became similar again. Sub-system 5b (WBCWBL) had consistently lower average barley yields than other sub-systems from 2011 onwards. All three other sub-systems (2c, 3c, 4c) had very similar annual barley yields and followed the same yearly trends. Except for in 2013, when the average barley yields from 2c (PPB) increased, whilst those from 3c (PWPB), 4c (PPWB) and 5b (WBCWBL) decreased. As seen for the wheat yields, the barley yields also recovered quickly in 2020 after the drought in 2019, showing the systems had increased in resiliency over the trial period.

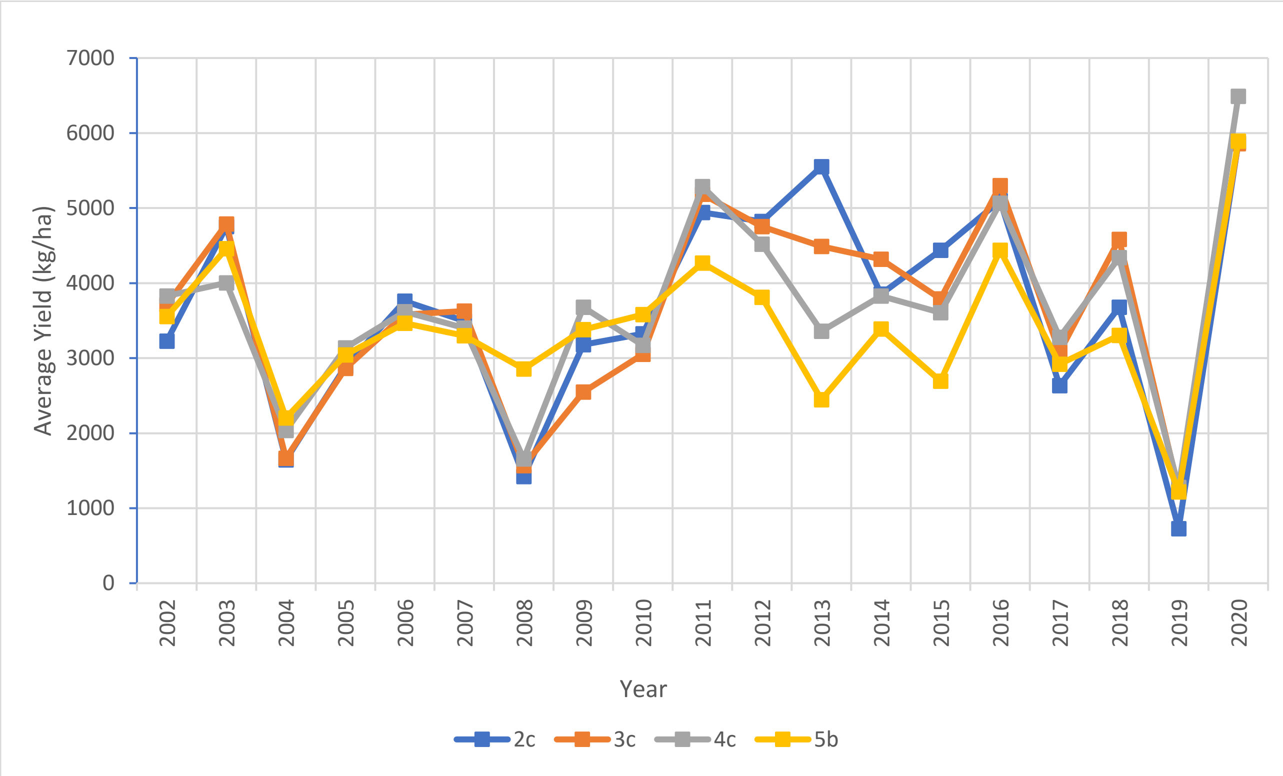


Figure 4.16 - The average annual barley yields per sub-system from 2002-2020.

The overall average barley yields for sub-systems 2c (PPB), 3c (PWPB) and 4c (PPWB) over the 19-year trial period are all very similar, with sub-system 5b (WBCWBL) being an outlier with a far lower average yield (Figure 4.17).

These results clearly showed how the inclusion of a legume crop (pastures in this case) had beneficial effects on the barley yields in a system. Each year of the trial, a single nitrogen top dressing was given to each crop. The amount of nitrogen given differed between crops but not between systems. This could be why the systems that had a nitrogen-fixing crop planted the year prior to a cash crop (such as barley) showed higher overall average yields, as extra nitrogen was available in the soil. Continuous cash cropping systems such as 5b (WBCWBL) did not have the added benefit of nitrogen-fixing pastures, and therefore may have suffered from nitrogen deficiencies, causing the lower yields seen from these systems. Sub-system 5b (WBCWBL) did contained lupine, which is a legume capable of nitrogen fixation. However, lupine is always planted before wheat and then only followed by barley in sub-system 5b, meaning the additional nitrogen added by the lupine was predominantly used by the wheat, leaving less for the subsequent barley crop.

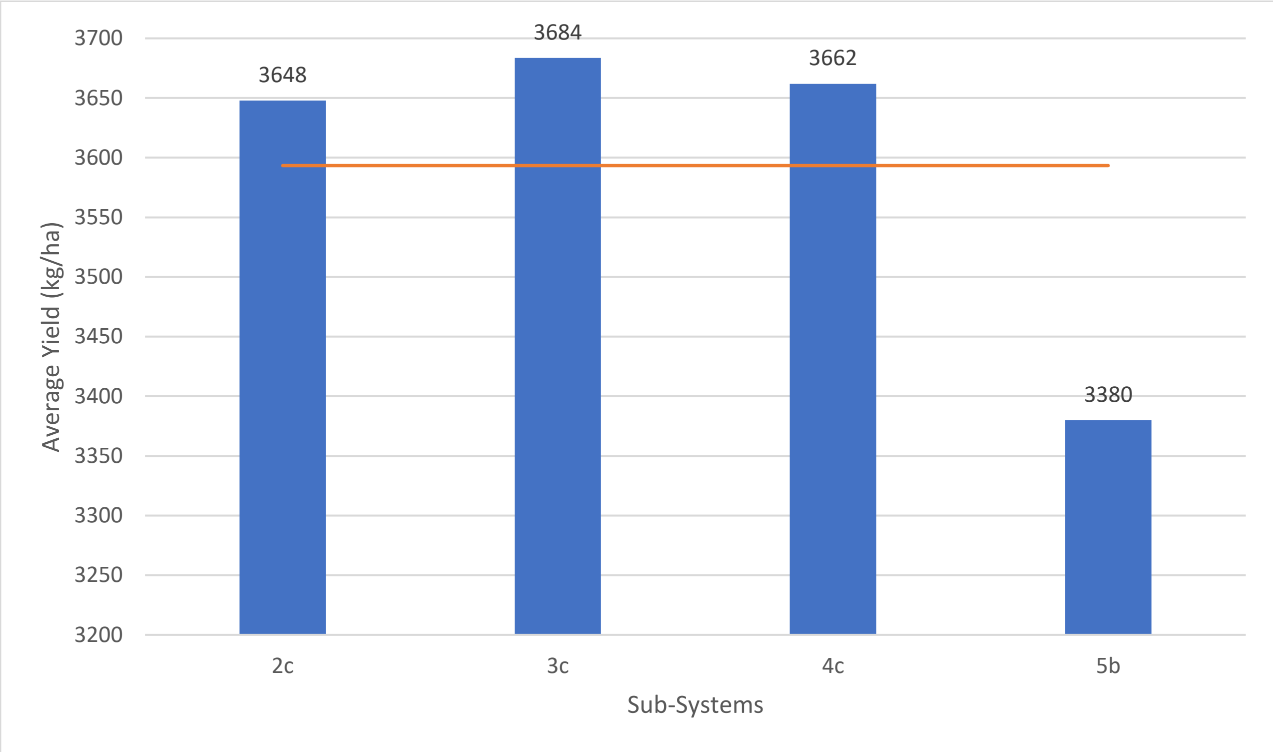


Figure 4.17 - The overall average barley yield for different sub-systems over a 19-year period from 2002-2020. The line depicts an overall average cost of all sub-systems tested.

4.4.1.3) Yields for Different Three-Year Barley Sequences

The barley yields from the five different three-year crop sequences (Figure 4.18) were similar until 2010, after which more variation in yields between the sequences was seen until 2017, after which the yields became comparable again. The average barley yields of the crop sequences containing pastures (PPB, PWB and WPB) were usually higher than those without pastures (CWB and LWB). This could be due to the additional nitrogen available to barley following the leguminous pastures.

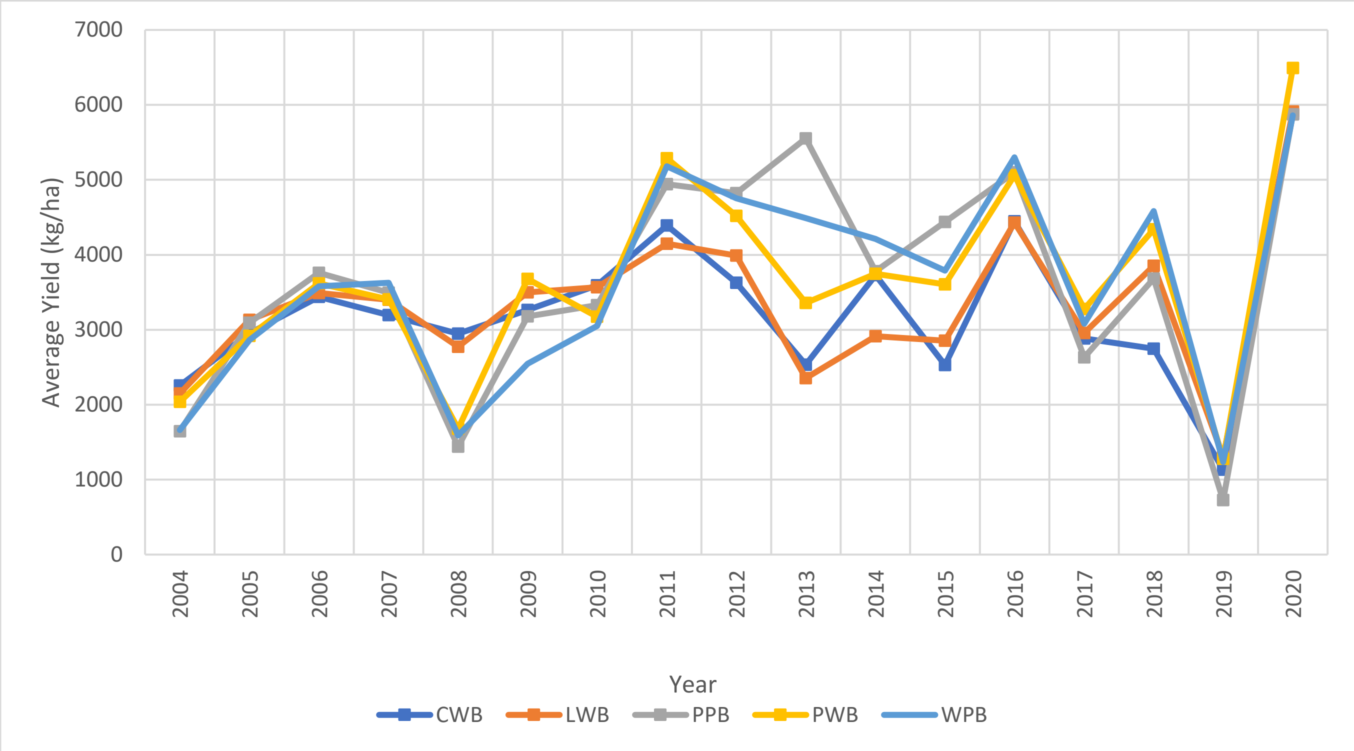


Figure 4.18 - The average annual barley yields for different three-year crop sequences from 2004-2020.

The highest maximum barley yield over the 17-year period was 6 491 kg/ha from the crop sequence PWB in 2020. The lowest barley yield, 726 kg/ha, was from crop sequence PPB in 2019, which could be attributed to low rainfall that year. The crop sequence PPB had the highest average barley yield over the entire trial period (3 617 kg/ha).

Figure 4.19 illustrates the overall average barley yields from different three-year crop sequences. The average barley yields from crop sequences with a pasture component are very similar and are all higher than the yields of crop sequences without a pasture component. This may once again be due to increased nitrogen fixation during the pasture year. The highest yielding crop sequence was PPB, but this was still only slightly higher than WPB and PWB, as the yields from all three of these sequences were very similar. The average overall barley yields from crop sequences CWB and LWB were both considerably lower than those of the other sequences, with the average yield from sequence CWB being slightly lower than that from LWB.

Figure 4.19 - The overall average yields of barley from different three-year crop sequences over a period of 17-years from 2004-2020

Although the average overall barley yields from crop sequences WPB, PWB and PPB were all very similar, the coefficient of variation between the three sequences was different, meaning the variation between yields for each of the sequences differed. The coefficient of variation is: "a normalised value of the standard deviation calculated as the ratio between the standard deviation and the mean. It has the advantage of being unit-free and it can be interpreted as a sort of "average" deviation or average 'shock' in the value as a percentage of the mean." (Kimura *et al.,* 2010). Crop sequence PPB had the highest coefficient of variation, meaning it had the most variation in yields over the years, so although PPB had the highest average yield the yields from this crop sequence were the most erratic. Crop sequence LWB had the lowest coefficient of variation, but also the second lowest average yield. Although the average yields of crop sequences PPB and PWB were very similar, PWB has a lower coefficient of variation, meaning yields were more stable. Overall, due to the similarity of PPB, PWB and WPB, any of these three combinations will work when aiming to achieve higher yields.

The barley yields for different four-year crop sequences had very similar trends to those of the three-year sequences and were therefore not included.

4.4.2) Barley Quality

Barley quality is determined by a few different characteristics, namely varietal purity, germination, protein content, moisture, plumpness, amount of peeled or damaged kernels and the presence of mycotoxins and disease (Macleod, 2010). The quality of the barley is determined, to a large extent, by the cultivation practices followed during production. These can include the level of nitrogenous fertiliser used, cultivar choice, seeding rates and dates, previous crop residue and tillage practices (Kassie & Tesfaye, 2019). There are only two barley grades, namely, feed grade and malt grade. Malt grade is the higher quality barley that is used for brewing purposes and human consumption whilst feed grade is a lower quality barley which is mainly used in animal feed. For this thesis the plumpness and nitrogen content of barley were used as measures of quality. The exact parameters used to grade barley can be found in Chapter 3.6.

4.4.2.1) Plumpness

The plumpness of barley kernels is an important measure of quality as plump kernels contain higher levels of starch, which will produce more beer from a given mass of malt (Macleod, 2010). A sieve with a certain hole size (usually 2.5 mm) is used to determine kernel plumpness (ARC, 2019). The barley is placed on the sieve and shaken, the percentage of kernels retained by the sieve determines the plumpness of the barley ("Barley Requirements", 2021). Cultivar choice has a big impact on barley plumpness, as do climatic conditions (ARC, 2019).

To be graded as malting grade, the barley plumpness will need to be above 70%. As can be seen in Figure 4.20 below, the overall average barley plumpness for all systems (the linear average line) increased steadily over the trial period, from just below 85% in 2002 to around 90% in 2020.

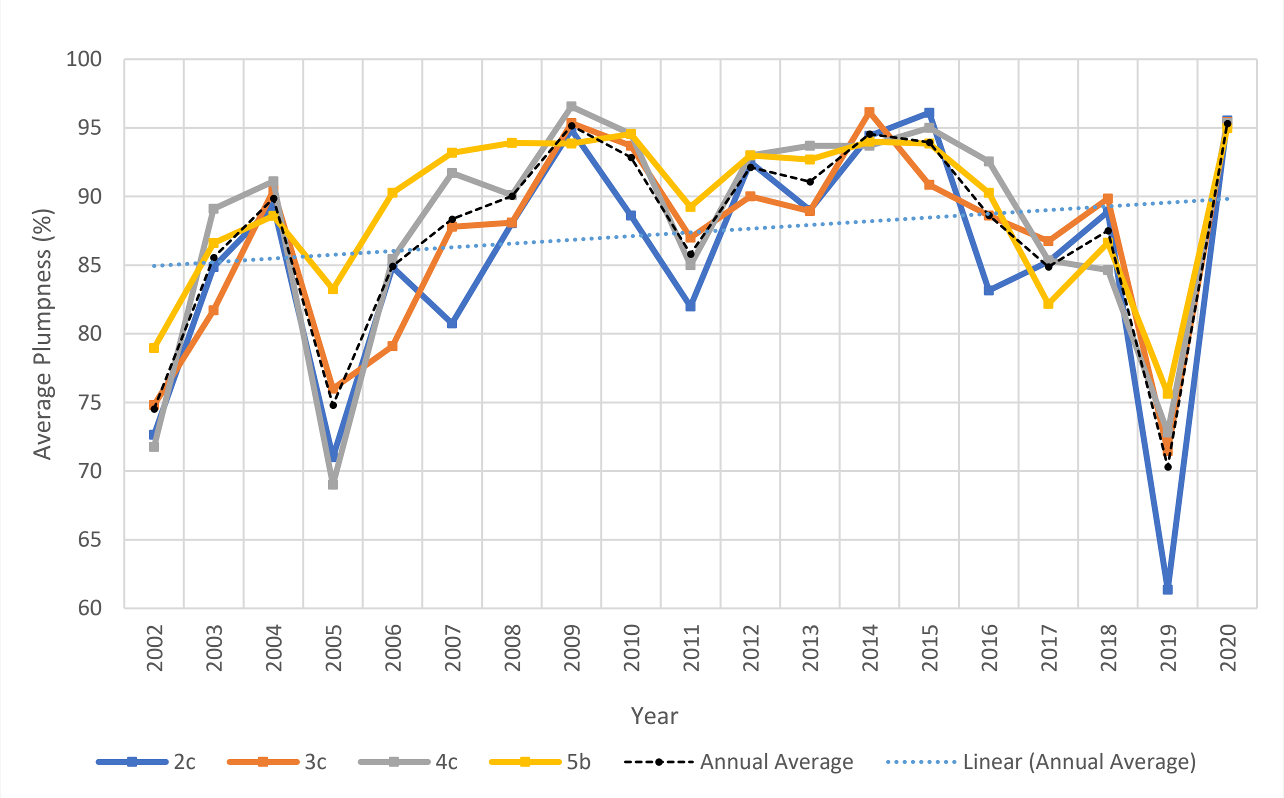


Figure 4.20 - The average plumpness of barley from different sub-systems from 2002-2020.

Barley from sub-system 2c (PPB) often had below average plumpness whilst barley from sub-system 4c (PPWB) and 5b (WBCWBL) often had above average plumpness, which might be due to there being less nitrogen in these systems. The average barley plumpness was varied during the first few years of the trial and dropped substantially in 2005 and 2019. From 2006 until 2018 the barley plumpness remained fairly stable, whilst all sub-systems achieved an average that ranged between just above 80% and just over 95%. After the big drop in 2019, the average plumpness for all sub-systems rose again to just above 95%. The increase in plumpness may have been influenced by the particular sub-system within which the barley was planted as well as an improved cultivar selection and good rainfall that year.

4.4.2.2) Nitrogen Content

The nitrogen content of a barley kernel is a direct indication of its crude protein content. Protein content and plumpness are the main determining factors for the speed at which barley goes through the malting process (Hertsgaard *et al.*, 2008). The nitrogen content of barley can be influenced by genetics as well as the environment. Some cultivars are known to have lower nitrogen content in the kernel, even with higher nitrogen fertilisation in the soil which usually increases nitrogen content. This is a valuable characteristic in a cultivar, as it is not only high nitrogen fertilisation that increases kernel nitrogen content, but also environmental factors such as drought and the nitrogen supply capacity of the soil, which is where soil tillage and the preceding crop become important (ARC, 2019).

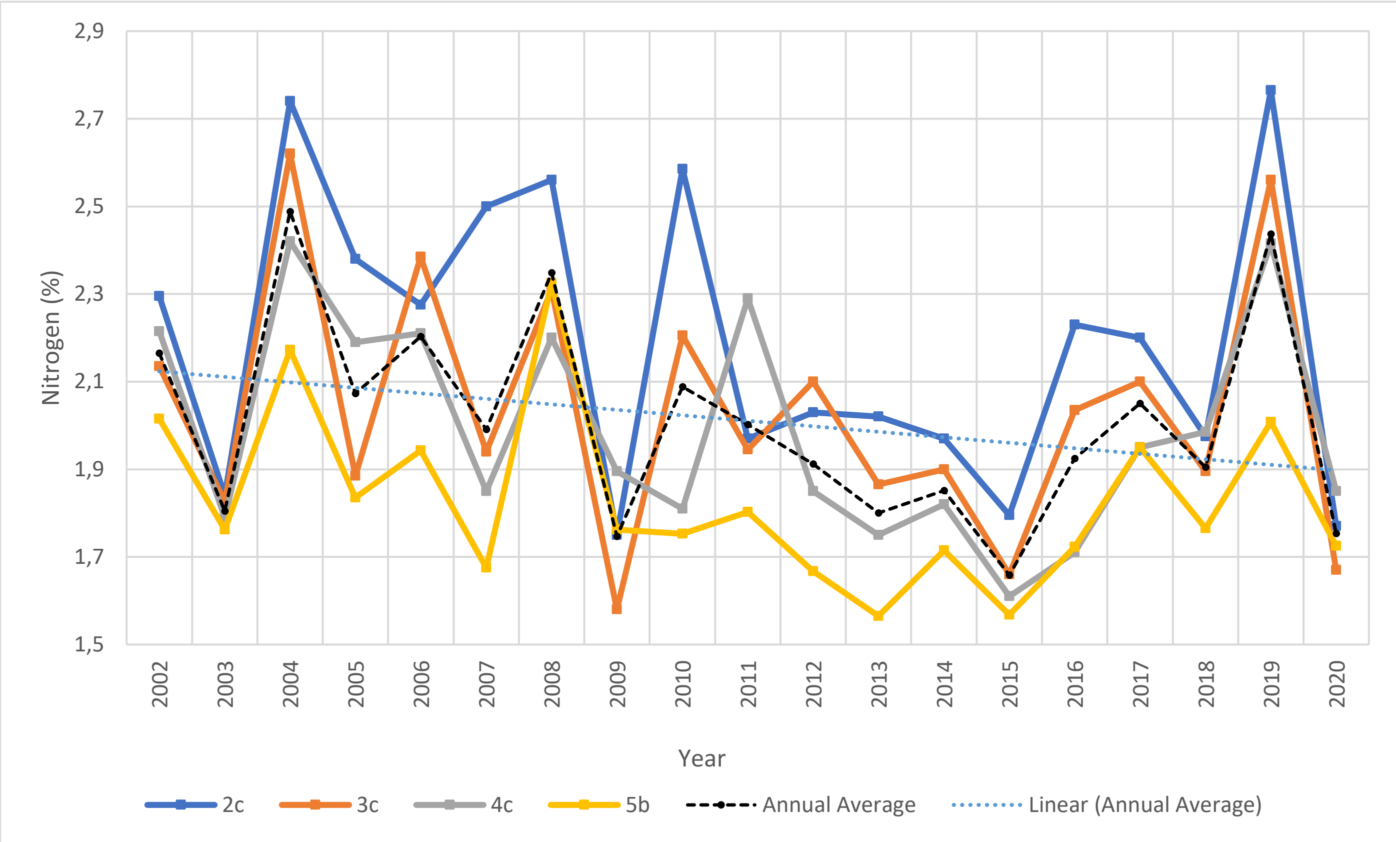


Figure 4.21 - The average nitrogen content of barley from different sub-systems from 2002-2020.

To be graded as malting grade, the nitrogen content of barley should be between 1.5 and 2.0%. If the nitrogen content is above or below those levels, the barley will be graded as feed. As illustrated in Figure 4.21, the overall average nitrogen content of barley from all sub-systems (the linear average line) decreased over the trial period, from just above 2.1% in 2002 to around 1.9% in 2020. This is an improvement in the average barley quality as it puts the average nitrogen content further within the bounds required to be graded as malting grade. The average nitrogen content of barley from sub-system 5b (WBCWBL) was consistently lower than the overall average and lower than that of barley from all other sub-systems. This may be due to sub-system 5b (WBCWBL) having only had one legume year (lupine) in a six-year rotation which resulted in less nitrogen in the soil when compared to other sub-systems. The lower nitrogen content in the soil will lower the nitrogen content of the barley planted in this sub-system. Barley from sub-system 2c (PPB) had consistently higher nitrogen content than barley from all other sub-systems and was regularly above average. This might have been caused by the two pasture years in the sub-system, with only one cropping year within which the extra nitrogen could be used. The higher levels of nitrogen in the soil during this cropping year increased the nitrogen content of the barley. Initially, the nitrogen content of barley from all sub-systems was varied and the sub-systems differed greatly from each other, but as time went on (from about 2010 onwards) it became more similar and often achieved malting grade.

4.4.2.3) Plumpness, Nitrogen Content & Ratings

Figure 4.22 shows the overall average plumpness, nitrogen content and ratings of barley from different sub-systems over a 19-year period. The rating system that was used is outlined in Chapter 3.6.

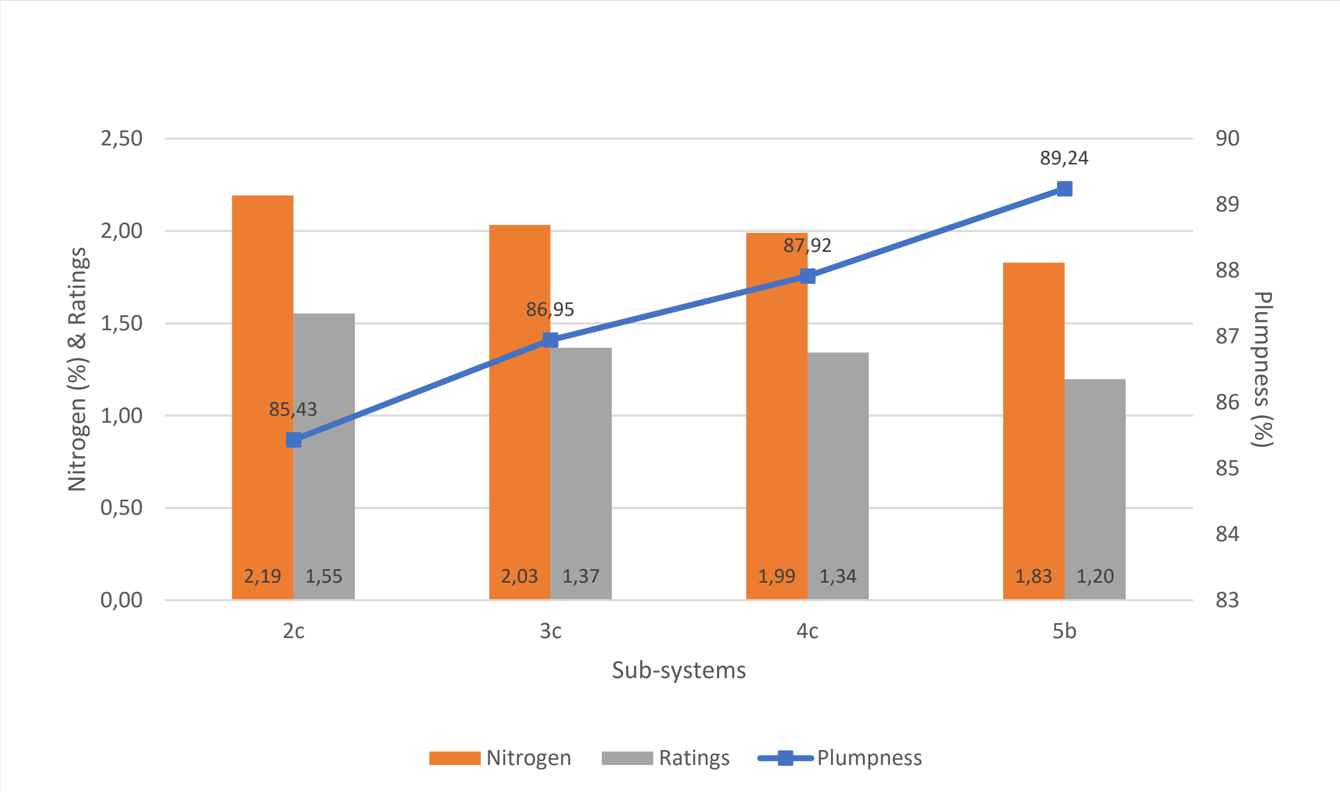


Figure 4.22 - The plumpness, nitrogen content and ratings of barley in different sub-systems over a 19-year period from 2002-2020.

Barley from sub-system 2c (PPB) had the lowest average plumpness and highest average nitrogen content, whilst barley from sub-system 5b (WBCWBL) had the highest plumpness and lowest nitrogen content. Barley from all sub-systems had an average plumpness that was above the 70% required to be classified as malting grade. However, a nitrogen content of between 1.7 and 2.0 % is needed in conjunction with the plumpness requirements. Barley from sub-systems 3c (PWPB), 4c (PPWB) and 5b (WBCWBL) met the nitrogen requirements for malt grade. However, the nitrogen content of barley from sub-system 2c (PPB) was slightly too high, which meant it would be classified as feed grade. Barley from sub-system 5b had the lowest overall average rating, which meant it was the best quality barley on average. Barley from sub-system 2c (PPB) had the highest overall average rating which meant that barley from this sub-system was usually lower quality than barley from other sub-systems.

4.5) Canola Yields

4.5.1) Canola Yields over time

There was a slight increase in the overall canola yields over the trial period (linear average line) from below 1 500 kg/ha in 2002 to nearly 1 500 kg/ha in 2020 (Figure 4.23).

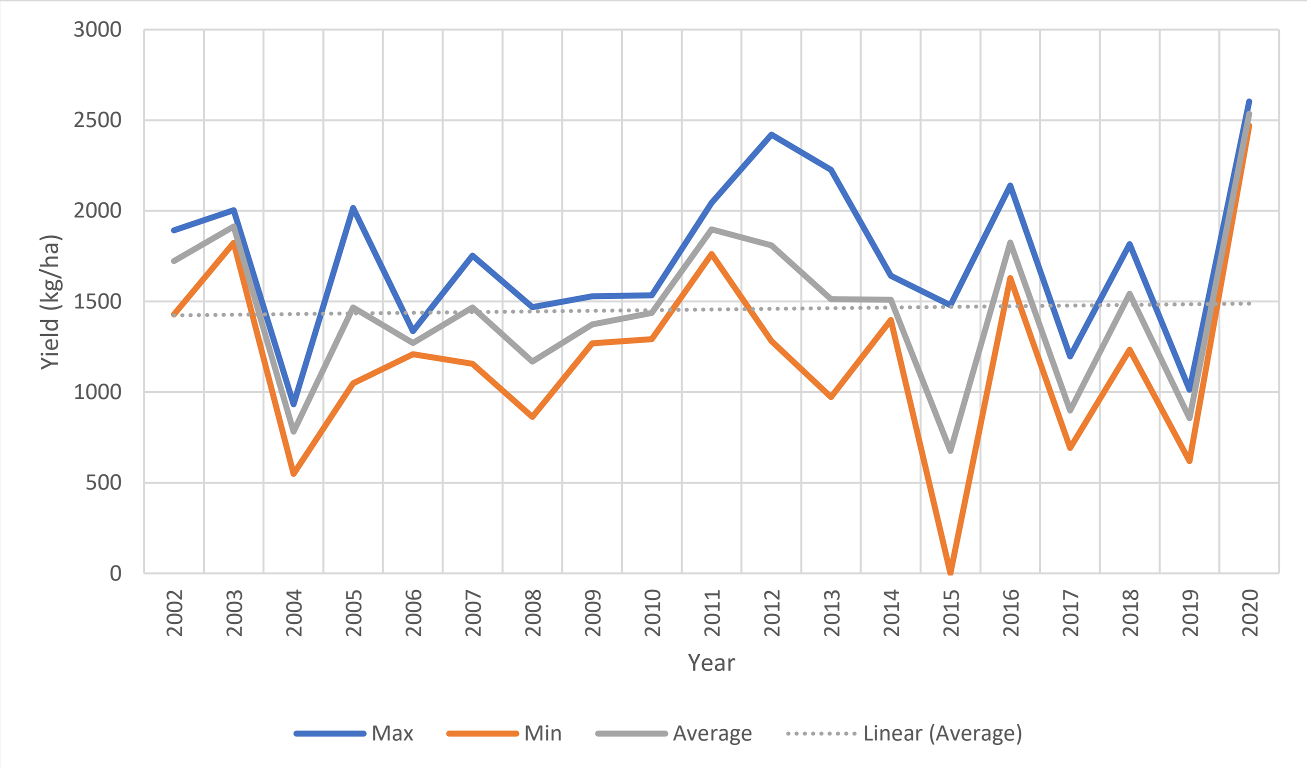


Figure 4.23 - The maximum, minimum and average annual canola yields from 2002-2020.

The minimal increase over time could be strongly influenced by cultivar choice, as the main cultivars of choice over the trial period were Triazine Tolerant (TT) canola cultivars. TT canola is better for weed control purposes as it is tolerant to the triazine group of herbicides, but is also associated with having approximately 20% lower yields than non-TT cultivar canola (Robertson *et al.*, 2002). This yield difference is caused by the low photosynthetic performance associated with tolerance to triazine herbicides, which is a result of inefficient photochemistry. The performance of TT cultivars is being improved upon and better varieties are becoming more readily available but slightly lower yields can still be expected when using this cultivar choices.

The lowest minimum canola yields were seen in 2004, 2015 and 2019. The reason for the zero minimum in yields seen in 2015 was that canola from sub-systems 3d (PWPC) and 4d (PPCW) was not able to be harvested due to strong winds destroying the crops. Therefore, only canola from sub-systems 5a (WCWL) and 5b (WBCWBL) was harvested in 2015. The highest maximum canola yields were seen in 2012, 2016 and 2020. The lowest average canola yields were in 2004, 2015 and 2019 and the highest average yields were in 2003, 2011 and 2020. The low average yields in 2004 and 2019 could be attributed to low amounts of growing season rainfall. There was considerable variability in the data during the earlier years of the trial, but this decreased from 2016 onwards.

4.5.2) Canola Yields per sub-system

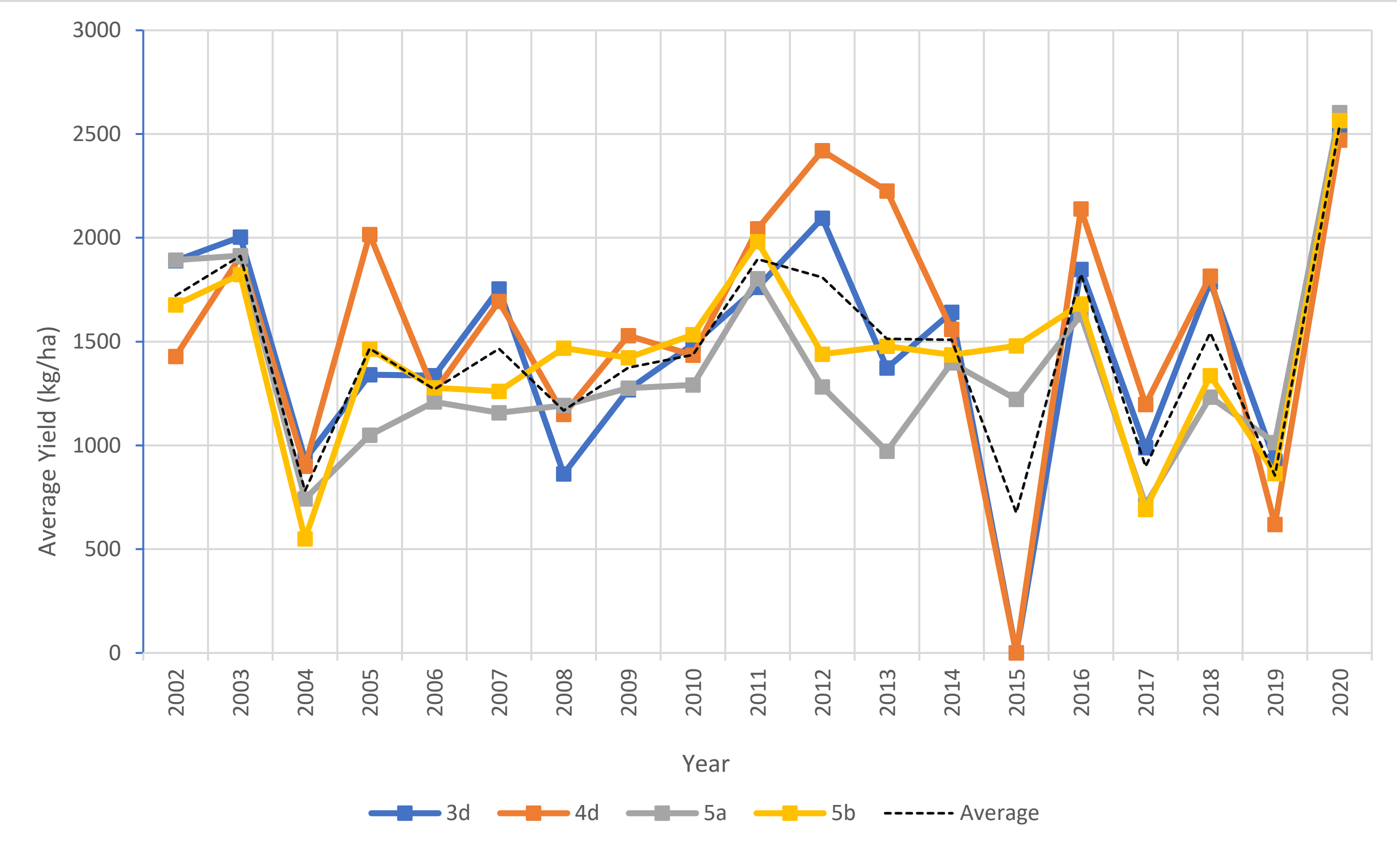


Figure 4.24 - The average annual canola yield per sub-system from 2002 - 2020.

The yields of the different sub-systems were similar until 2011, they became more varied from 2011 until 2016, after which they became comparable yet again (Figure 4.24). In 2015, the average canola yields of sub-systems 3d (PWPC) and 4d (PPCW) were zero, as only the canola produced in the cash crop sequences (5a and 5b) were harvested. Sub-systems 3d (PWPC) and 4d (PPCW), which both included two pasture years, often achieved above average yields, with 4d often being higher than 3d. This could be attributed to the extra nitrogen available to canola from these sub-systems from the leguminous pastures. Sub-systems 5a (WCWL) and 5b (WBCWBL), the continuous cash-cropping sequences, often had below average canola yields with yields from 5a being lower than those from 5b from 2005 until 2016 when the yields of the two sub-systems become very similar for the rest of the trial period. The reason for the lower average canola yields from sub-system 5a (WCWL) may have been due to the one repetition of sub-system 5a planted in camp 11, which had poor quality soil, which resulted in lower yields.

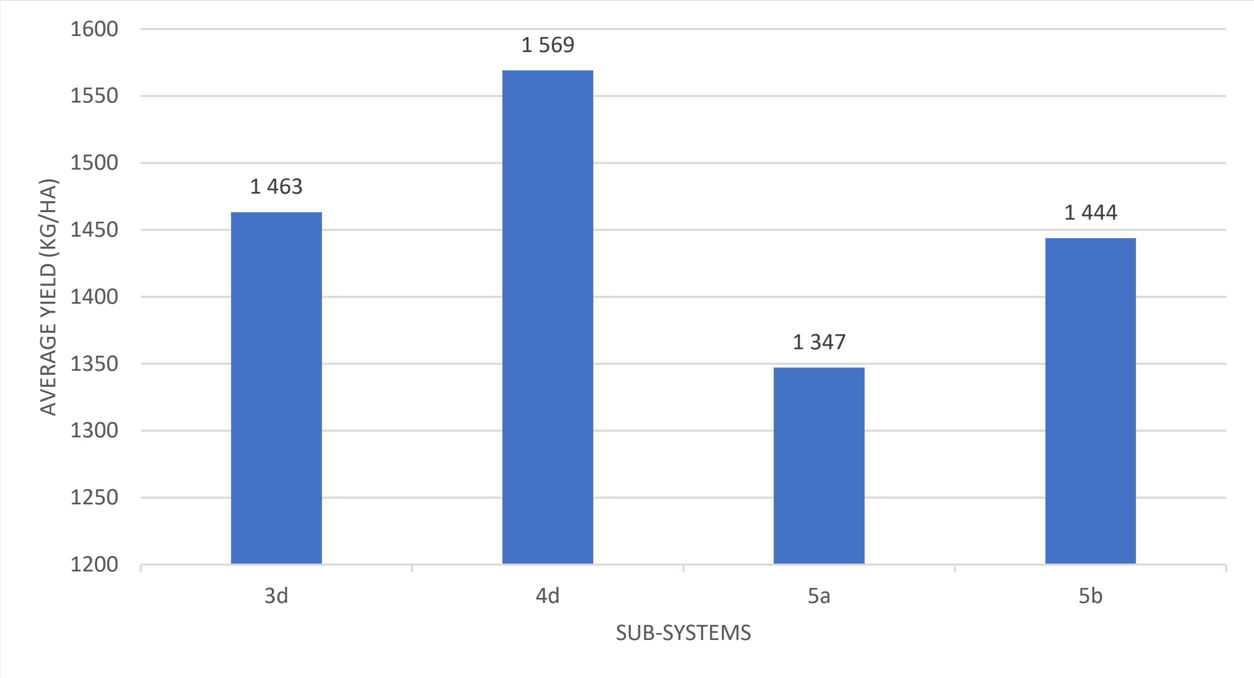


Figure 4.25 - The overall average canola yields per sub-system over a 19-year period from 2002-2020.

The overall average canola yields for the different sub-systems are illustrated in Figure 4.25. Canola from system 4d (PPCW) had the highest overall average yield, followed by canola from system 3d (PWPC) and 5b (WBCWBL), which both had very similar overall average yields. System 5a (WCWL) had the lowest overall average yield. The lower yield for sub-system 5a might once again be due to the repetition planted in camp 11 achieving lower yields in general. Sub-system 4d (PPCW) had by far the highest overall average canola yield. This was possibly due to the two consecutive pasture years, preceding the canola year, which added extra nitrogen into the soil to that could be used by the subsequent canola crop. This extra nitrogen might have been a principal contributing factor to the higher yields seen in sub-system 4d.

4.5.3) Canola Four-Year Sequences

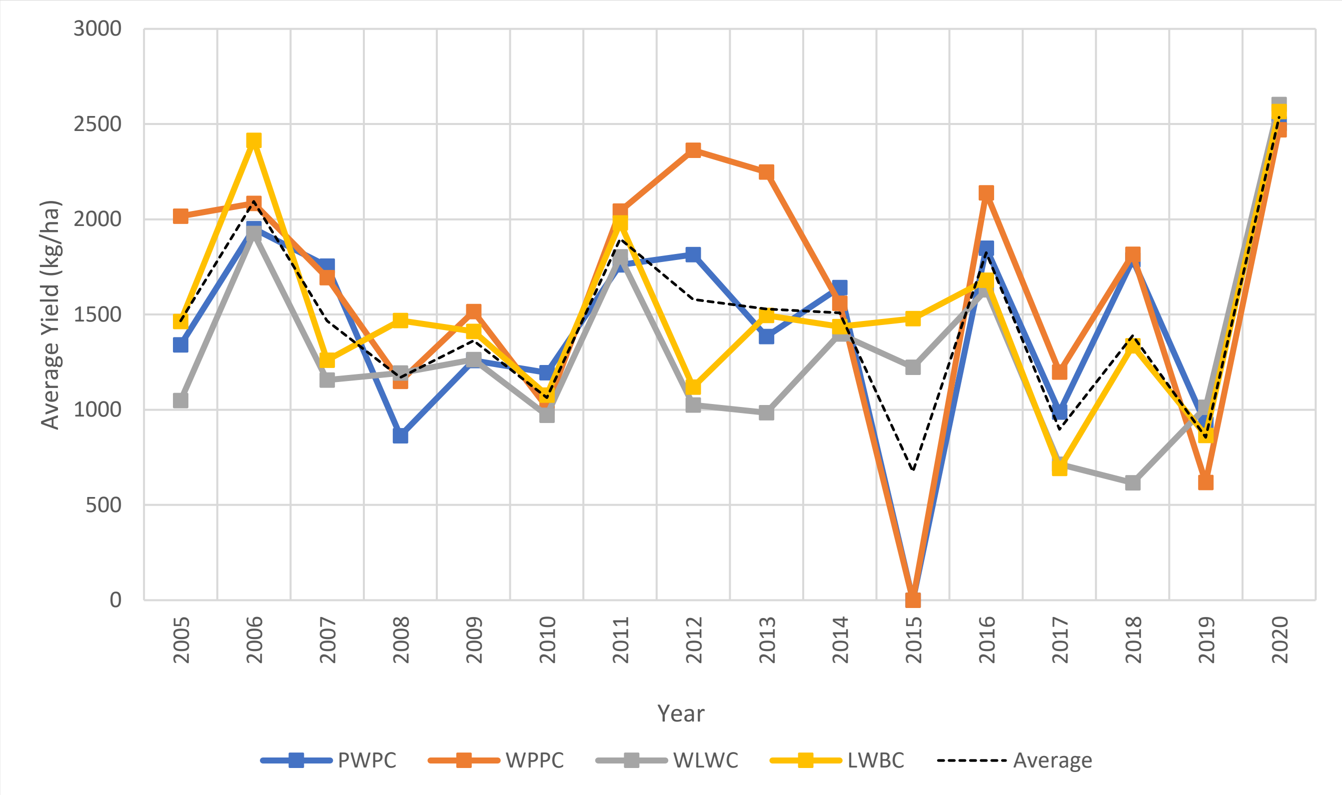


Figure 4.26 - The average annual yield of canola from different four-year crop sequences from 2005-2020.

The average annual canola yields of each of the four-year canola sequences are illustrated in Figure 4.26. The average yields of the different four-year canola sequences were comparable until 2011, after which they diverged until 2016, then became similar again until the end of the trial period. Crop sequence WPPC had a predominantly higher than average yield except for in 2015 and 2019. Crop sequence WLWC most often had a lower than average yield except for in 2015. This can be attributed to sequence WLWC being part of sub-system 5a, some of which was planted on camp 11 which has lower yields than other camps due to soil type. The average canola yields from crop sequences PWPC and WPPC were from sub-systems 3d and 4d, with these being the canola camps that were not harvested due to strong winds in 2015. This is the reason for the yields of these sequences being zero in 2015.

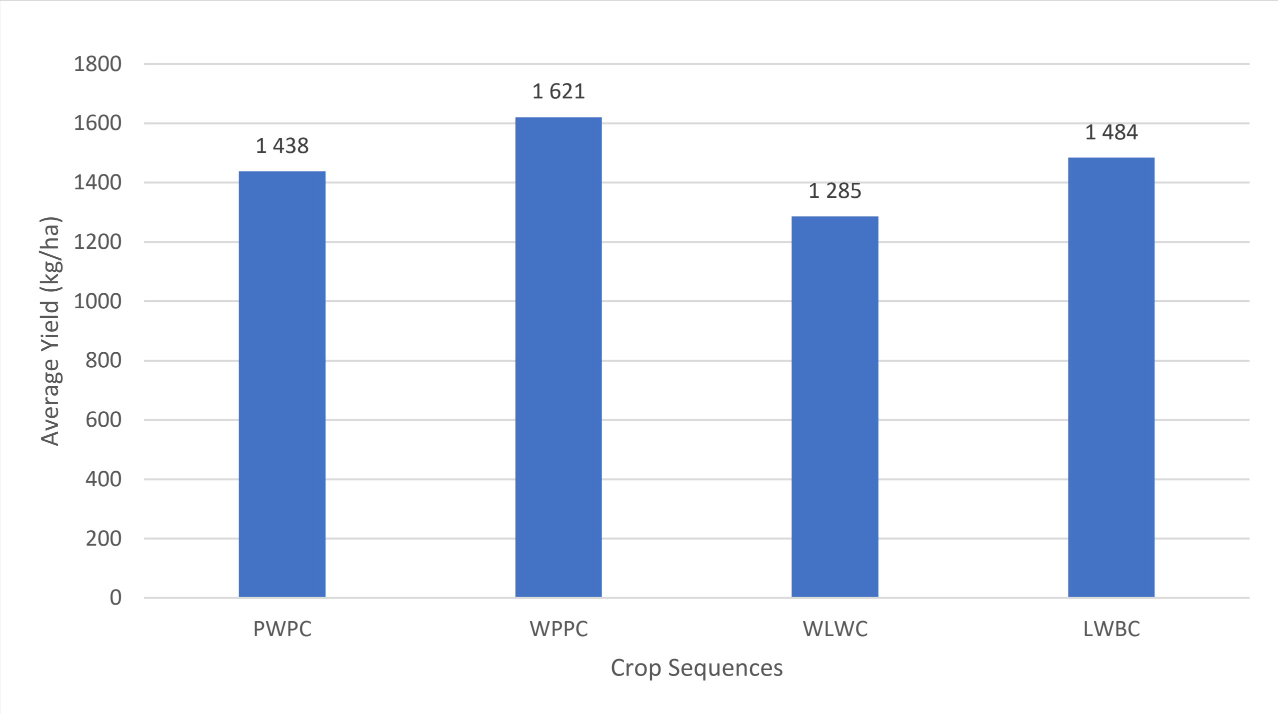


Figure 4.27 - The overall average yield of canola from different four-year crop sequences over a 16-year period from 2005-2020.

As shown in Figure 4.27, the average yields from all crop sequences varied between 1 250 kg/ha and 1 650 kg/ha. Crop sequence WPPC had the highest overall average canola yield, followed by LWBC and PWPC. The average canola yields from sequences PWPC and LWBC were very similar, but LWBC was slightly higher. However, the canola yields of crop sequences PWPC and WPPC was slightly lower due to no canola being able to be harvested for these sequences in 2015 because of the wind damage. The yields of these sequences may have been higher if not for this unfortunate climatic event as both sequences contained two pasture years which would have supplied extra nitrogen to the canola in these sequences, which may have been a contributing factor to the higher yields. Canola from crop sequence WLWC had the lowest overall average yields, but as mentioned before, canola from this sequence came from sub-system 5a, some of which was planted on camp 11 with consistently lower yields.

4.6) Conclusion

Chapter 4 examined the yield and quality data collected from the short rotation systems at Tygerhoek Experimental Farm from 2002 until 2020. Climatic conditions, cultivar choice and camp location within the trial were seen to be the dominant factors regarding crop yields and quality. The amount and dispersion of rainfall throughout the year impacted crop yields with drier years usually having lower yields. However, the systems did seem to show increased resiliency to drought conditions over time after years of being under CA management. This was illustrated by the quick bounce-back of crop yields in 2020 after three consecutive drought years, with 2019 having had record low yields. Another overriding factor that impacted yields, was the location of camps within the trial layout. Sub-system 5a (WCWL) had one repetition in camp 11 that had self-compacting soil which notably impacted yields from this camp with consistently lower yields than those for the repetition planted in camp 18 with better soils. Cultivar choice also played a role, as more suitable cultivars became more readily available, yields increased accordingly.

The three crops focused on in this chapter were wheat, barley and canola. The yield data for all three was examined but the quality data was only discussed for wheat and barley. Wheat was the most popular crop and was a component of most sub-systems. The wheat yields for the different systems were similar in the earlier years of the trial with differences between systems only becoming more apparent over time. Sub-system 5a (WCWL) had lower wheat yields than other sub-systems which can once again be attributed to the lower soil quality of camp 11. The highest yielding wheat sub-systems all included two pasture years, either consecutively or staggered, in rotation with two crop years – one of which was wheat. These were sub-systems 3d (PWPC), 4d (PPCW) and 3b (PWPO). The higher yields seen for wheat following pastures can, in part, be attributed to the additional nitrogen available to the crop as the pastures contained nitrogen-fixing legumes. The pasture year also allowed for better weed control before the wheat year, reducing the competition from weeds which allowed for higher yields. Two of the three highest yielding wheat sub-systems had canola as the second crop in the four-year sequence. This may also have improved weed control preceding the wheat year, as certain weeds associated with wheat can be sprayed for during canola years as well as pasture years. This will further break down the weed seed bank, which has positive benefits for the wheat crop as weed issues are further reduced.

The three lowest yielding wheat sub-systems were 5a (WCWL), 4a (PPWW) and 5b (WBCWBL). Sub-systems 5a and 5b were continuous cash cropping systems and did not have the additional soil nitrogen that systems containing pastures did and had high levels of weed infestation. Sub-system 4a (PPWW) had two years of wheat monoculture (WW) which is also known to increase weed infestations as well as disease build-up, both of which can negatively impact yields. This was further emphasised by the yield results of the different three- and four-year wheat sequences, where sequences containing two wheat years often had lower yields. Those sequences containing pasture years usually had higher yields than sequences that didn't include a pasture year.

The wheat quality indicators considered in this thesis were hectolitre mass (HLM) and protein content. The overall average HLM of wheat in all sub-systems increased over time, whilst the average protein content decreased over time. On average, wheat from all the systems met the HLM requirements to be graded as BS (super grade) but the average protein content for system 5 was lower than the required level to be graded as BS, resulting in wheat from system 5 being graded as

B1 on average. Once again, the sub-systems containing pastures (systems 2, 3 and 4) produced higher quality wheat on average than the continuous cash cropping sub-systems (system 5).

There are only four sub-systems that include barley, namely 2c (PPB), 3c (PWPB), 4c (PPWB) and 5b (WBCWBL). The average barley yields for all four sub-systems were comparable at first, but the differences between sub-systems became apparent sooner than for the wheat sub-systems. The average barley yields for sub-system 5b (WBCWBL) dropped below those of the other sub-systems from 2010 onwards and showed considerably lower overall average yields when comparing yields over the 19-year trial period. The sub-systems including pastures, outperformed the continuous cash cropping sub-system (5b) in both wheat and barley yields. The average barley yields from different three-year crop sequences also showed higher yields for those sequences containing pastures than for those that did not. This may also be due to the increased soil nitrogen levels and lower weed prevalence in systems containing pastures.

The quality indicators used for barley, were kernel plumpness and nitrogen content. The overall average kernel plumpness increased over the duration of the trial whilst the average nitrogen content decreased. Sub-systems 3c (PWPB), 4c (PPWB) and 5b (WBCWBL) all met both the plumpness and nitrogen content requirements to be classed as malting grade. Sub-system 2c (PPB) met the plumpness requirements, but the average nitrogen content of the barley from this sub-system was slightly too high, resulting in it being rated as feed grade. This could be attributed to the double pasture years with only one cropping year. The higher levels of soil nitrogen following the pasture years may have caused the nitrogen content of the following barley crop to increase past the level permitted for malt grade.

There were also only four sub-systems that included canola, namely 3d (PWPC), 4d (PPCW), 5a (WCWL) and 5b (WBCWBL). Cultivar choice played a big role in the overall trends in canola yields over time. TT cultivars were mainly used during the trial which are associated with an estimated 20% lower yield than non-TT cultivars but do have less weed problems. In 2015, strong winds destroyed canola from sub-systems 3d (PWPC) and 4d (PPCW) which reduced the overall average yields for these sub-systems. The sub-systems including pastures, namely 3d (PWPC) and 4d (PPCW), had higher overall average canola yields than the continuous cash cropping sub-systems 5a (WCWL) and 5b (WBCWBL). However, the average canola yields for 5a (WCWL) were lower than those for 5b (WBCWBL) which might have been caused by the one repetition of sub-system 5a planted in camp 11. The overall average yield of sub-system 5b (WBCWBL) was only slightly lower than those of 3d (PWPC) and 4d (PPCW).

Overall, all three crops from the continuous cash cropping systems (system 5) had lower overall yields than systems including pastures (systems 2, 3 and 4). This may be linked to the improved soil nitrogen availability following leguminous pastures, as well as the reduced weed pressure associated with crops following pasture years.

Chapter 5 – Gross Margins and Input Costs Results and Discussion

5.1) Introduction

The main objective of this study was to determine the critical drivers for the long-term sustainability of different crop rotation systems in the Overberg. One major component of sustainability is profitability as this will ultimately determine whether an operation is able to remain successful over time. In chapter 5, the profitability of the different crop rotation systems incorporated in the trial at Tygerhoek Experimental Farm will be discussed. The profitability of the different rotation systems will be compared for gross income, allocatable variable costs, gross margins and input costs between systems over time.

Firstly, the gross income (GI), allocatable variable costs (AVC) and gross margin (GM) data for the rotation systems will be investigated. The systems in general will be compared over time and then the individual crops will be compared over time, in terms of GM, AVC and GI. The sub-systems for each individual crop will then be compared and analysed.

The input cost data will then be considered with the input costs for all sub-systems over time being compared first. The input costs for wheat, barley and canola are then compared as well as the difference in input costs between sub-systems for each of these crops. This is followed by an analysis of the main input costs per crop over time: fertiliser, weed control, seed and fungicide. The changes in the individual input costs over time for all sub-systems will be compared last to evaluate the changes in these inputs over the entire trial period.

One of the main aims of CA is to improve general soil health, reducing the need for external inputs whilst maintaining good yields, increasing the overall sustainability of an agricultural system and lowering the impact that the system has on the environment (Hobbs *et al.*, 2008). The use of CA principles aims to reduce input costs over time, allowing for higher gross margins and increased profitability which are crucial for long-term sustainability.

Table 5.1 below is a summary of the systems and sub-systems being compared and analysed in this chapter. A more in-depth description can be found in Chapter 3.

Table 5.1 - Crop rotation systems and sub-systems at Tygerhoek Experimental farm.

System	Sub-Systems
System 2 (67% annual legume pastures: 33% crops)	• 2a – PPW • 2b – PPO • 2c – PPB

System 3 (50% annual legume pastures; 50% crops)	○ 3a – PWPW ○ 3b – PWPO ○ 3c – PWPB ○ 3d - PWPC
System 4 (50% annual legume pastures; 50% crops)	▪ 4a – PPWW ▪ 4b – PPOW ▪ 4c – PPWB ▪ 4d – PPCW
System 5 (100% crops)	▫ 5a – WCWL ▫ 5b - WBCWBL

5.2) Gross Margin Data

The gross income (GI), allocatable variable costs (AVC) and gross margins (GM) for different crops and different sub-systems will be compared and discussed in this section. All three of these values were recorded for every crop in every sub-system each year from 2002 until 2020. One of the main factors driving the profitability of these short rotation systems is yield, as discussed in Chapter 4. The higher the yield, the higher the gross income. Reduced input costs also play a role in increasing profitability, as this will lower the allocatable variable costs for the systems. With an increased gross income from higher yields and lower allocatable variable costs due to reduced inputs, higher gross margins can be achieved for the short rotation systems discussed below.

5.2.1) Gross margin data for all systems & sub-systems

5.2.1.1) Gross Margin Data for Sub-systems

The sub-systems with the highest GI over the entire trial period were 4c (PPWB), 5b (WBCWBL) and 3a (PWPW). The average GI of these sub-systems ranged between R 6 975 and R 6 821/ha (Figure 5.1). The sub-systems with the lowest GI were 2b (PPO), 5a (WCWL) and 2c (PPB), respectively. In the initial years of the trial, oats were planted for haymaking purposes. In the later years, oats were cultivated to be sold to the breakfast cereal market which pays a better price. This may be the reason for the low overall average GI seen for sub-system 2b (PPO). There was a difference of R 1 139/ha between the average GIs of the top and bottom three sub-systems. The sub-systems with the highest AVCs were 5a (WCWL), 5b (WBCWBL) and 3a (PWPW). The high AVCs seen for sub-systems 5a (WCWL) and 5b (WBCWBL) are due to these sub-systems being made up of only cash crops. Cash crops usually require higher input levels for inputs such as weed control and fertiliser when compared to pastures. Sub-system 5a (WCWL) also had one repetition planted in camp 11, which was known to have more weed control issues and lower soil quality than other camps. This increased the average AVCs for the cash cropping sub-systems. The sub-systems with the lowest average AVCs were 2b (PPO), 2c (PPB) and 2a (PPW), respectively. There was a difference of R 518/ha between the average AVCs of the top and bottom three sub-systems. The sub-systems with the highest overall average GM were sub-systems 4c (PPWB), 3c (PWPB) and 3a (PWPW). The sub-systems with the lowest overall average GM were 5a (WCWL), 2b (PPO) and 3d (PWPC) respectively. There was a difference of R 990/ha between the average GMs of the top and bottom three sub-systems.

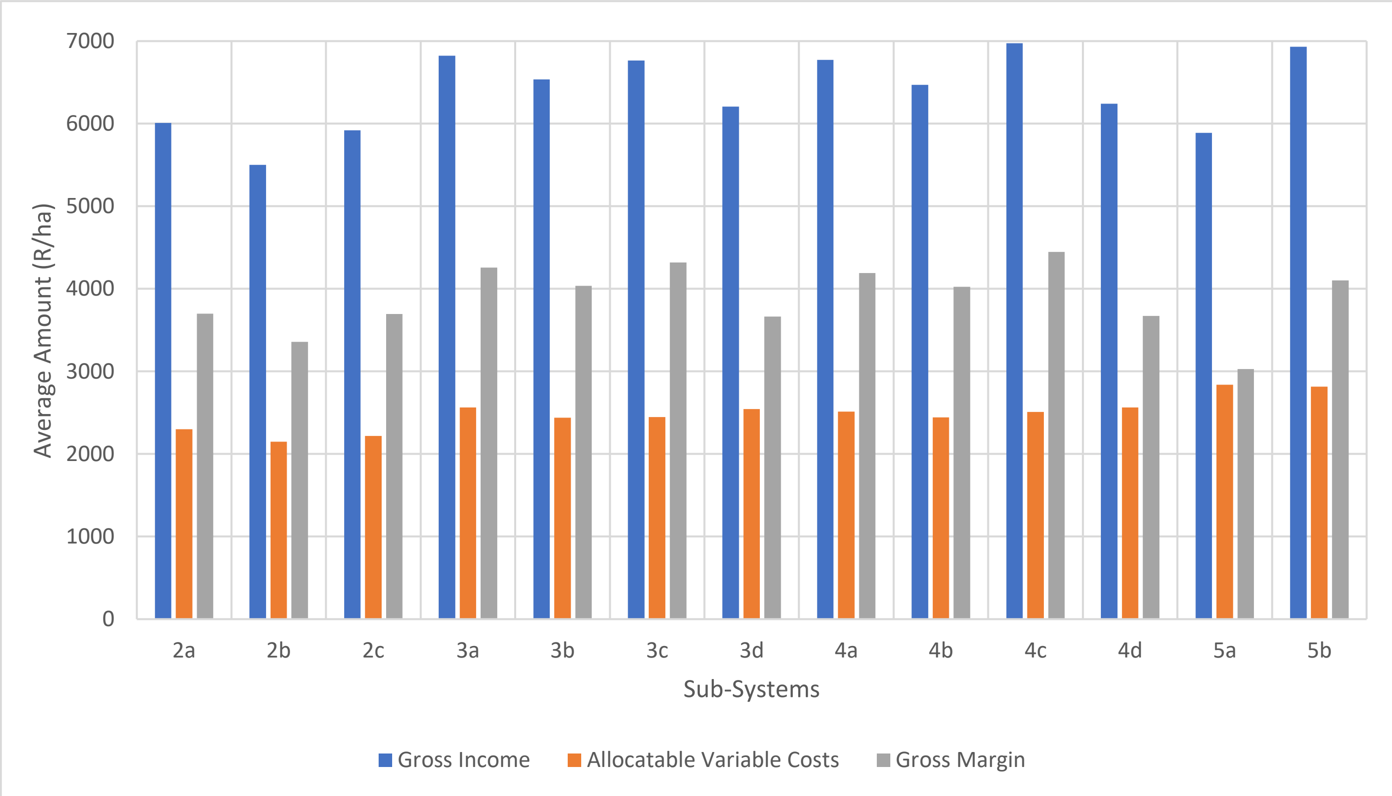


Figure 5.1 - The average gross income, allocatable variable costs and gross margins of different cropping sub-systems over a 19-year period from 2002 – 2020.

Sub-system 5a (WCWL) had the second lowest GI, the third highest AVC and the lowest GM overall. The poor performance seen from sub-system 5a could be attributed to the sub-system having lower crop yields, on average, than other sub-systems due to the one repetition planted in camp 11 which consistently showed lower yields than other camps. The high average GI seen in sub-system 5b (WBCWBL) can be explained by the higher amount of cash cropping years in this sub-system. Cash crops bring in higher income than pastures, where the income is only from the livestock (sheep). However, 5b (WBCWBL) also had some of the highest average AVCs which decreased the average GM.

5.2.1.2) Gross Margin Data for Main Systems

Only the four main rotation systems are shown in Figure 5.2 since the inclusion of all the sub-systems each year would make the interpretation of the data more difficult. Systems 3 and 4 often had a higher average GM than the other two systems. System 5 followed the trends of the other systems until 2017, when it started to decrease to far below the average GM of the other systems. System 5 was made up of only continuous cash crops and was far less sustainable over time than the other systems, all of which contain some form of nitrogen fixing crop/pasture in some years. System 5 was also the only system to ever achieve a negative gross margin.

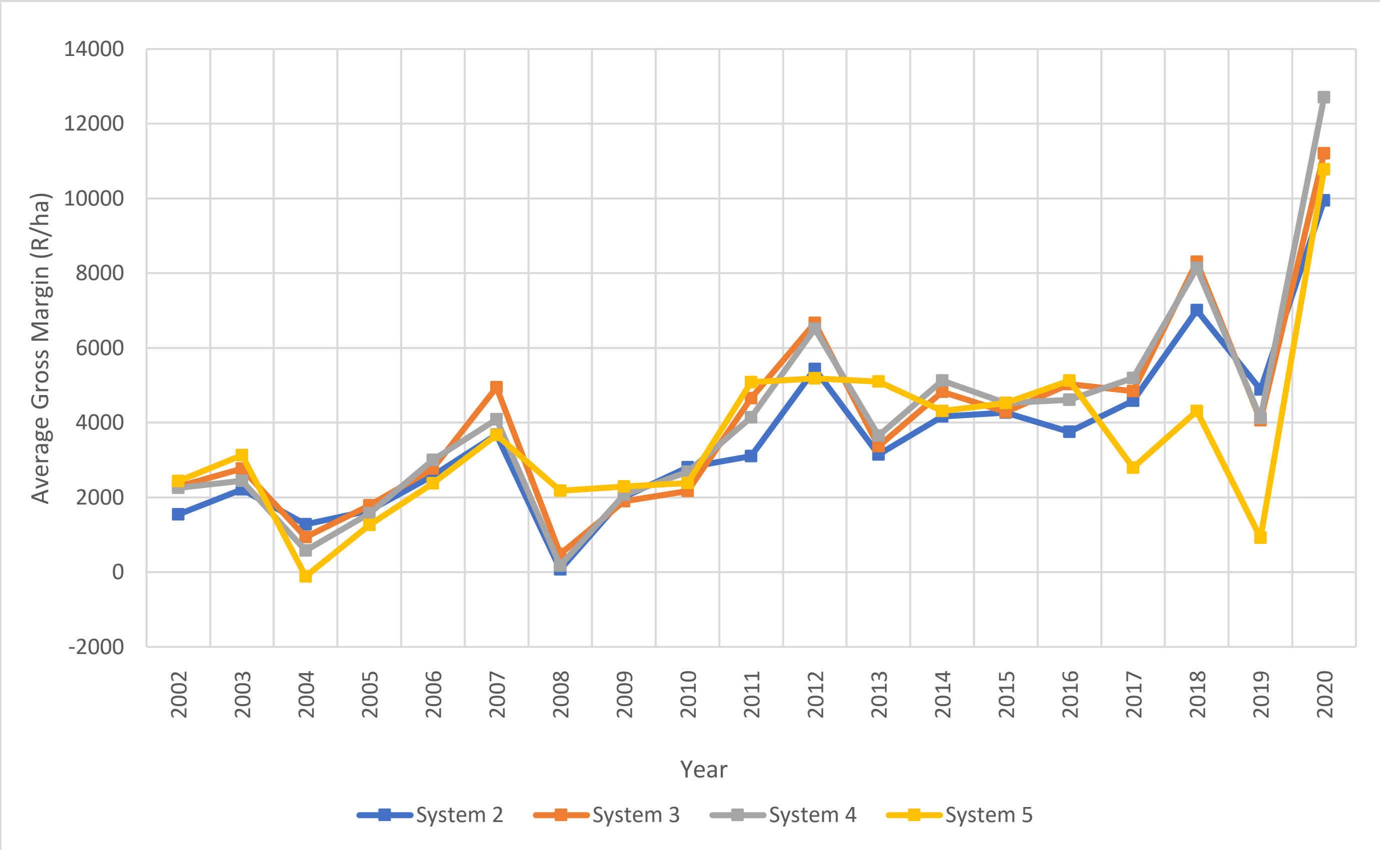


Figure 5.2 - Average annual gross margins of the four main short rotation systems from 2002 - 2020.

The general trend in average GMs was that they usually decreased when there was low growing season rainfall (detailed rainfall data can be found in Appendix 3). This was seen in 2003, 2004 and 2019, where the average GM for all the systems was very low. This can be attributed to lower yields in those years. However, as mentioned before, the amount of growing season rainfall is not the only factor to be considered. The dispersion of the rainfall throughout the growing season is very important. This was evident in 2020, where the average GM for all the systems reached an all-time high, even though the growing season rainfall was not excessively high. This was because the rainfall was distributed evenly throughout the 2020 growing season, resulting in record yields which increased the average GMs for all systems. The low GMs for systems 2, 3 and 4 in 2008 could be attributed to the lower yields and high input costs incurred that year, as well as the poor meat and wool prices for the sheep. In 2019, a major drop in average GMs was seen, this was caused by three successive dry years (2017, 2018, 2019), culminating in 2019 when there was a severe drought which lowered yields dramatically. Although the average GM for the systems declined in 2019 it did not fall as low as earlier dry years in the trial period, which showed an increase in the resiliency and sustainability of the systems over time.

5.2.2) Gross Margin Data for Different Crops over time

5.2.2.1) Wheat

Wheat was planted in 28 camps each year and was a component in all of the sub-systems except 2b, 2c and 2d. In sub-systems 3a, 4a, 5a and 5b wheat featured twice. Each phase of each sub-system was represented each year.

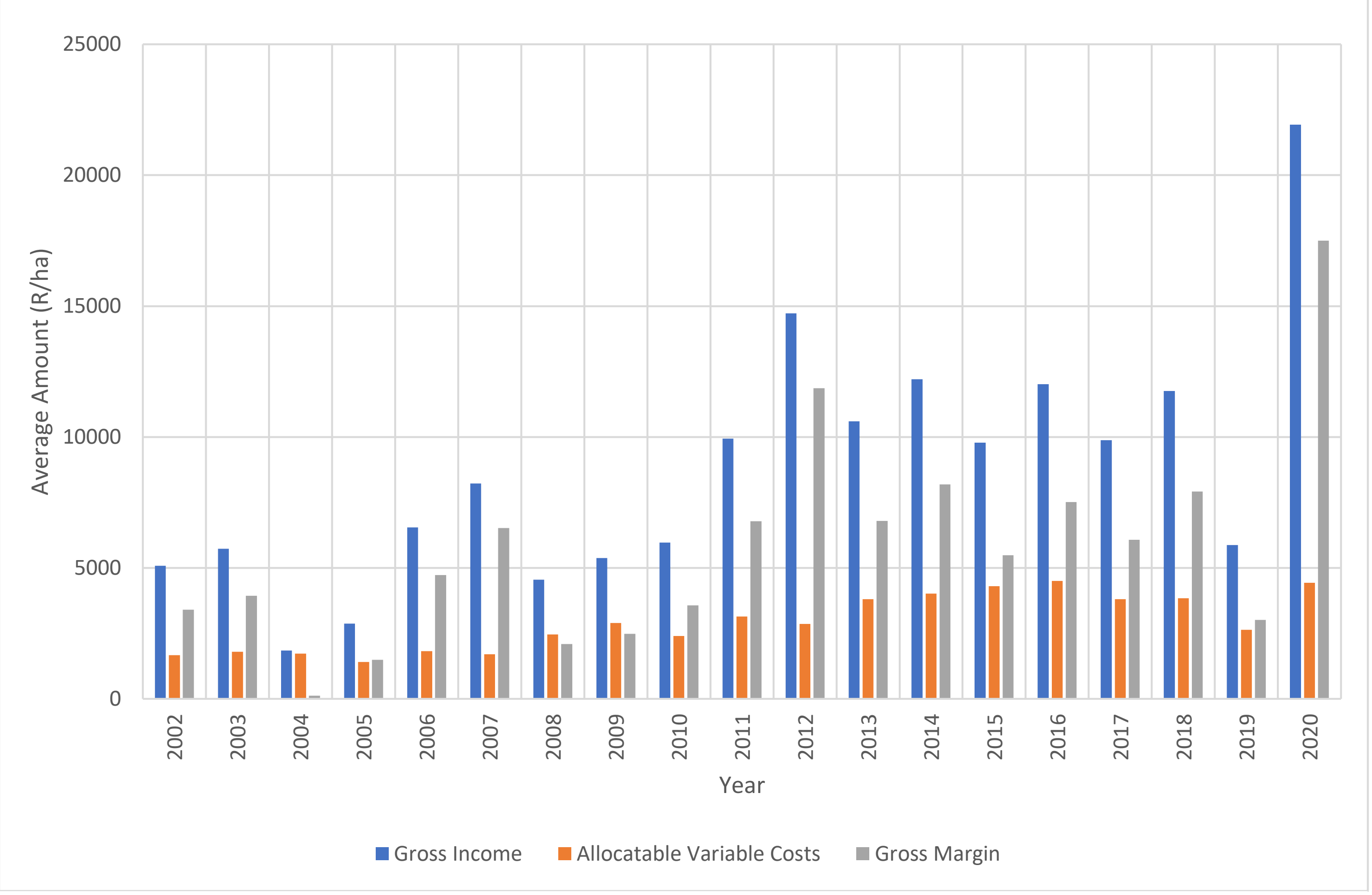


Figure 5.3 - The annual average gross income, allocatable variable costs and gross margins for wheat overall from 2002 until 2020.

In Figure 5.3, the average annual GI, AVC and GM for wheat each year from 2002 until 2020 is displayed. This included all the wheat data regardless of the system or sub-system that the wheat camp was part of. The average annual GI of wheat varied in the first few years of the trial, staying below R 10 000/ha until 2012, after which it ranged between R 10 000/ha and R 15 000/ha, with some years falling below the R 10 000/ha mark. One such year was 2019, which might have been caused by the severe drought experienced that year. The other two dry years were 2015 and 2017, both of which had an average annual GI below R10 000/ha. The highest average annual GI was in

2020 and the lowest was in 2004, when the GI was well below R 5 000/ha. The very low average GI in 2004 could also be attributed to it having been a very dry year with lower than usual wheat yields.

The average annual AVCs for wheat remained low until 2008/9, after which they increased gradually over time, dropping again in 2019, but increasing in 2020. The cost of inputs increased steadily over time, even though input levels may not have. This price increase was a notable contributor to the increase in average AVCs over the years. The highest average AVCs were in 2016 and the lowest were in 2005.

The average annual GM of wheat remained predominantly below R 5 000/ha until 2011, after which GM increased to above R 5 000/ha, except in 2019, when it dropped again. As mentioned before, 2019 was a very dry year and had low wheat yields which was a major contributing factor to the low average GI and GM seen. The highest average annual GM for wheat was in 2020 and the lowest was in 2004, which was also a very dry year with low wheat yields. There were record high crop yields in 2020 which contributed to the high average GI and GM that year.

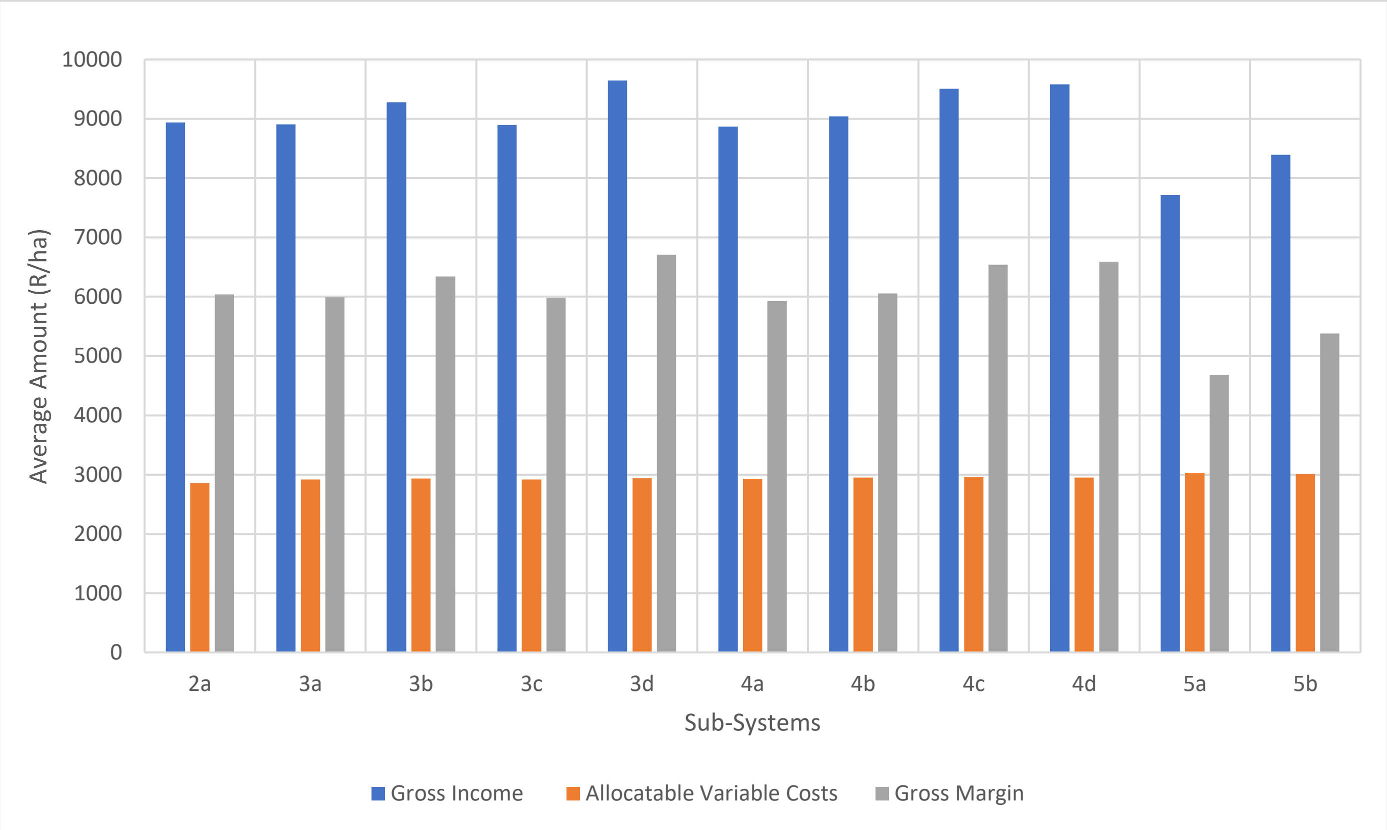


Figure 5.4 - The overall average gross income, allocatable variable costs and gross margins for wheat from different sub-systems over a 19-year period from 2002 until 2020.

Figure 5.4 illustrates the overall average GI, AVCs and GM of wheat from each sub-system that had a wheat component over the 19-year trial period. Most of the sub-systems had an average GI between R 8 000/ha – R 9 000/ha. Five sub-systems had an average GI above R 9 000/ha (3b, 3d, 4b, 4c, 4d). The sub-system with the highest average GI was 3d (PWPC), followed by 4d (PPCW) and 4c (PPWB). The sub-system with the lowest average GI was 5a (WCWL), followed by 5b (WBCWBL) and 4a (PPWW). It is evident that the average GI for wheat from sub-systems including pastures was, on average, higher than for those sub-systems without pastures. The only sub-system that included pastures, but still had a low average GI was 4a (PPWW), but this sub-system included two consecutive years of wheat. The first year of wheat from this sub-system may have had good yields due to the extra nitrogen from the leguminous pastures but yields dropped in the second year of wheat which may have been due to less nitrogen being available in the soil. There might also have been higher weed pressure in the second wheat year, as grass weeds may have prevailed from the year before.

The average AVCs were very similar across all wheat sub-systems, all of which were around R 3 000/ha. The sub-system with the highest average AVC was 5a (WCWL), followed by 5b (WBCWBL) and 4c (PPWB). The slightly higher AVCs seen for wheat from system 5 might have been caused by the increased weed pressure in the continuous cash cropping sub-systems which required additional weed control. The sub-system with the lowest average AVC was 2a (PPW), followed by 3c (PWPC) and 3a (PWPW). All these sub-systems included two pasture years, for which the average input costs were usually slightly lower than for crops. However, the differences in AVCs between sub-systems was very minimal when comparing the averages over 19 years. The AVCs of all sub-systems ranged between R 2 850/ha and R 3 035/ha.

Most of the wheat sub-systems had an average GM close to R 6 000/ha, with only 5a (WCWL) and 5b (WBCWBL) being markedly lower. The sub-system with the highest average GM was 3d (PWPC), followed by 4d (PPCW) and 4c (PPWB). All three sub-systems with the highest average GMs had two pasture years. Sub-system 3d (PWPC) and 4d (PPCW) both had two pasture years, one canola and one wheat year. This showed that this grouping of crops could be profitable in the long-term, as long as the pasture years were incorporated in the correct manner. This could be attributed to the extra nitrogen in the soil during the crop years, provided by the leguminous pasture years, which increased yields. The sub-system with the lowest average GM was 5a (WCWL), followed by 5b (WBCWBL) and 4a (PPWW). The two continuous cash cropping sub-systems (5a and 5b) had markedly lower average GIs than other sub-systems and slightly higher average AVC's, leading to the lower average GMs seen for these sub-systems. As mentioned before, sub-systems from system 5 often had high weed pressure and low soil nitrogen which lowered yields and increased input costs. Sub-system 4a (PPWW) had a lower average GI than majority of other sub-systems (except for 5a and 5b) which could have been caused by lower average yields caused by the wheat monoculture component of the crop sequence.

5.2.2.2) Barley

Barley was planted in 10 camps each year and was part of the crop sequences in sub-systems 2c, 3c, 4c and 5b.

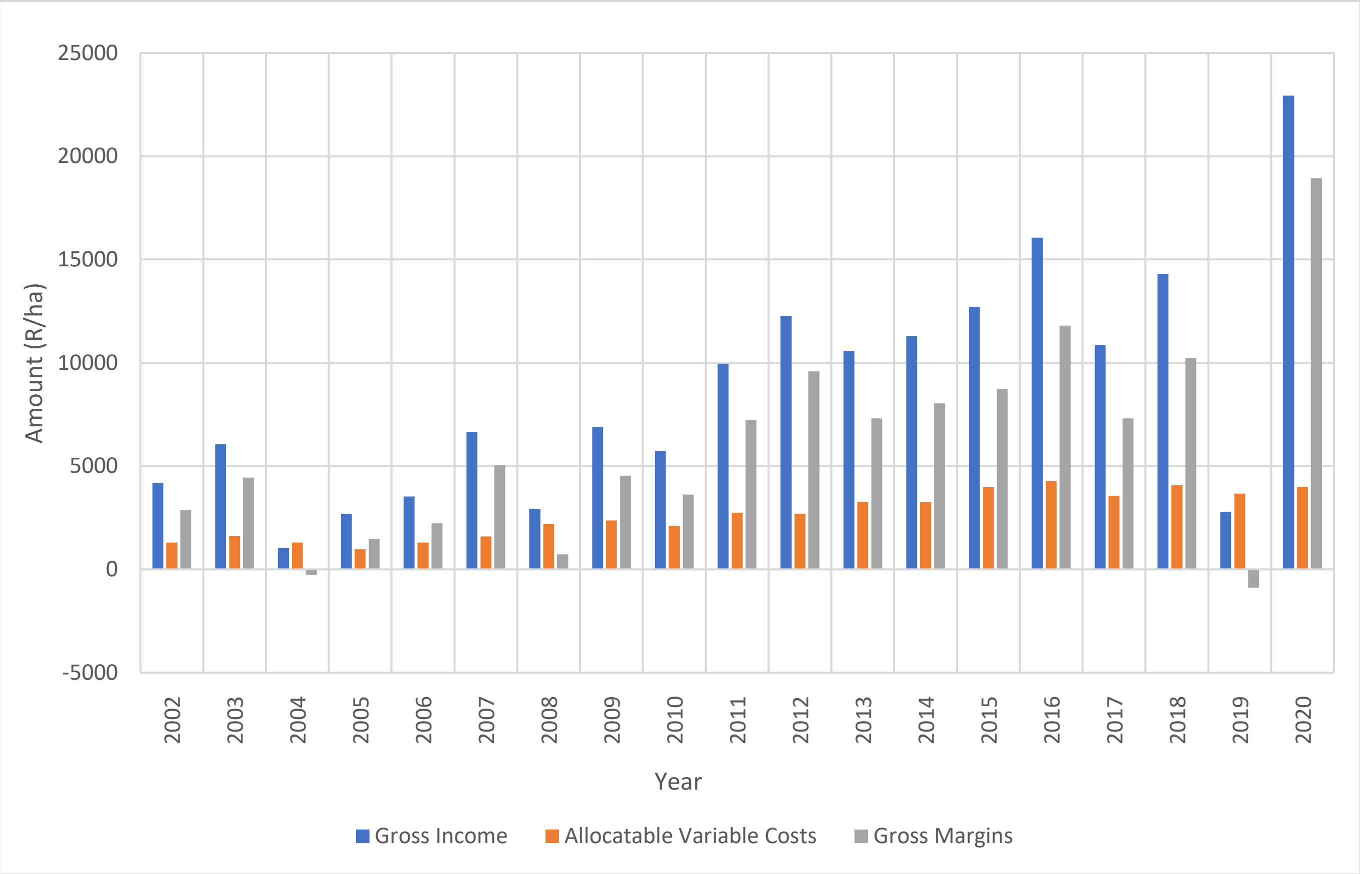


Figure 5.5 - The annual average gross income, allocatable variable costs and gross margins for barley overall from 2002 until 2020.

In Figure 5.5, the average GI, AVCs and GM for barley each year from 2002 – 2020 are shown. This includes all barley data regardless of the system or sub-system that the barley camp was part of. The average GI for barley remained around R 5 000/ha for the period between 2002 and 2010. The average GI in 2003, 2007, 2009 and 2010 however, was above R 5 000/ha, which may have been caused by lower commodity prices in these years. From 2011 onwards, the average GI increased to around R 10 000/ha and above. The average barley yields were seen to be markedly higher from 2011 onwards contributing to the higher average GI's. This could be attributed to the availability of new, better cultivar choices. However, the yields did drop in 2017 and 2019 due drought, which was reflected in the lower average GIs in those years. The lowest average GI was recorded in 2004, which was a very dry year with low yields. The highest average GI was in 2020 which could be attributed to the record high yields in that year.

The average AVCs for barley remained moderately low, well below R 5 000/ha, until around 2011, when they increased and came closer to the R 5 000/ha mark. The gradual increase in average AVCs was predominantly due to a general price increases for inputs over time. There was not much variation in the average AVC per year, as the years did not differ much. The highest average AVCs were recorded in 2016 and the lowest were recorded in 2005.

The average GM for barley varied from year to year. The average GM remained reasonably low, below R 5 000/ha, from 2002 until 2010, with a negative GM recorded in 2004. The growing season rainfall in 2004 was very low and this year followed on from another very dry year (2003). This negatively impacted yields, decreasing the average GI to below the average AVC, resulting in a negative GM in 2004. From 2011 onwards, the average GM increased to between R 5 000 and R 10 000/ha, being above R 10 000/ha in 2016, 2018 and 2020. This increase in average GMs can be attributed to new, improved cultivars becoming available, which in turn increased average barley yields and GIs while keeping average AVCs at a reasonable level. In 2019 however, there was a negative GM which was an outlier during the last ten years of the trial, but this was caused by the severe drought and very low yields in that year. The highest average GM was recorded in 2020 and the lowest was recorded in 2019.

The overall average GI, AVCs and GM for the different barley sub-systems over the entire trial period (19 years) are shown in Figure 5.6.

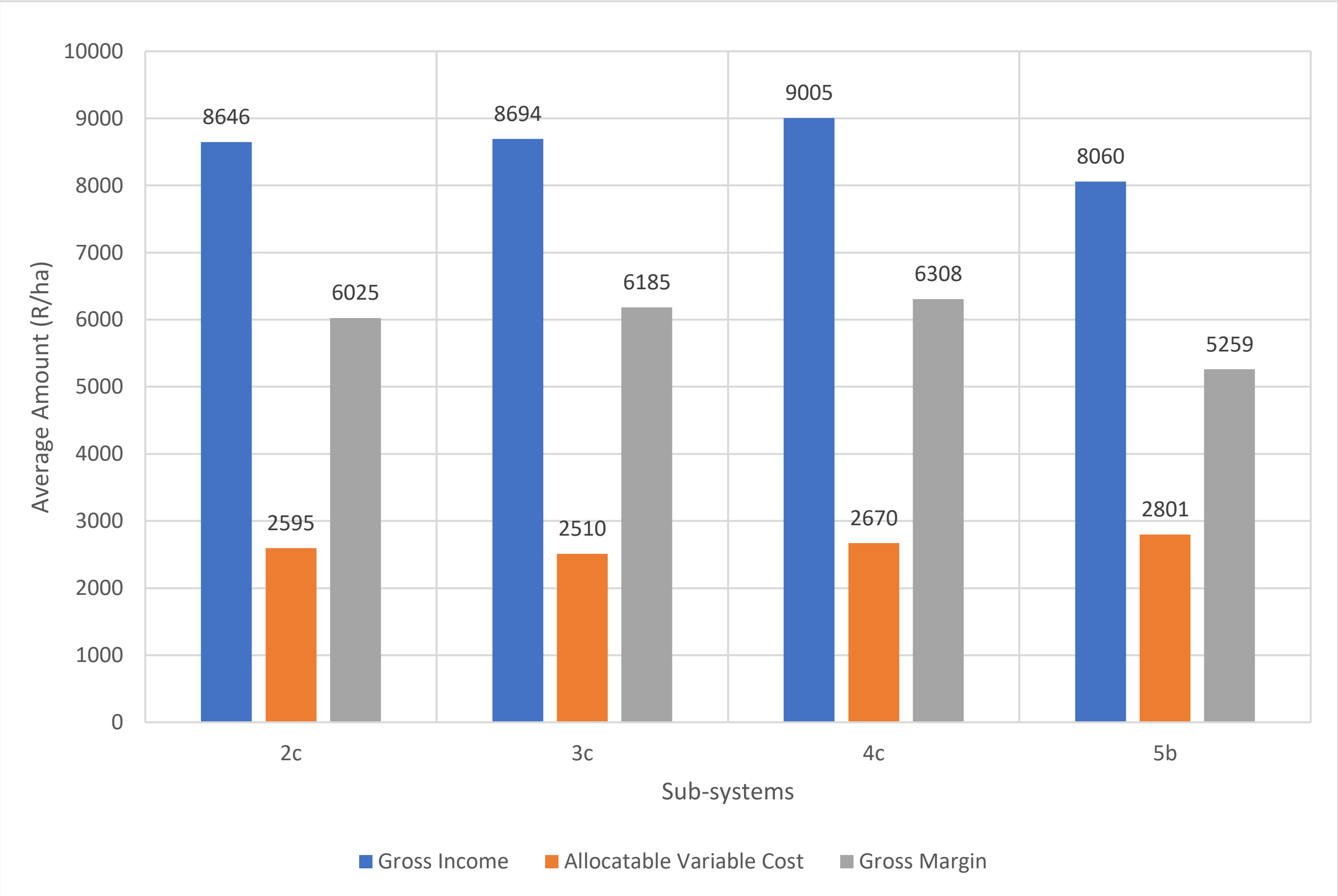


Figure 5.6 - The overall average gross income, allocatable variable costs and gross margins for barley from different sub-systems over a 19-year period from 2002 - 2020.

The overall average GI for all the sub-systems was above R 8 000/ha, with 4c (PPWB) being the highest at over R 9 000/ha. Sub-system 5b (WBCWBL) had the lowest average GI, only just above R 8 000/ha, whilst sub-systems 2c (PPB) and 3c (PWPB) both had average GIs above R 8 600/ha. Sub-system 5b (WBCWBL), the continuous cash cropping sub-system, had lower average barley yields than those sub-systems including a pasture element. The overall average AVCs were similar for all sub-systems, all being above R 2 500/ha but below R 3 000/ha. The lowest average AVCs were found in sub-system 3c (PWPB) and the highest were seen in 5b (WBCWBL).

The overall average GMs of sub-systems 2c (PPB), 3c (PWPB) and 4c (PPWB) were very similar, all being above R 6 000/ha. Sub-systems 2c, 3c and 4c all included a pasture element which increased the nitrogen available in the soil for the subsequent barley crop, increasing yields which increased the average GI of the sub-systems. Sub-system 5b (WBCWBL) however, had an average GM well below R 6 000/ha, closer to R 5 000/ha. However, this could be expected due to the lower average GI and higher average AVCs for this sub-system when compared to other sub-systems. The highest average GM was seen in sub-system 4c (PPWB).

5.2.2.3) Canola

Canola is planted in 8 camps each year and was part of the crop sequences in sub-systems 3d, 4d, 5a and 5b.

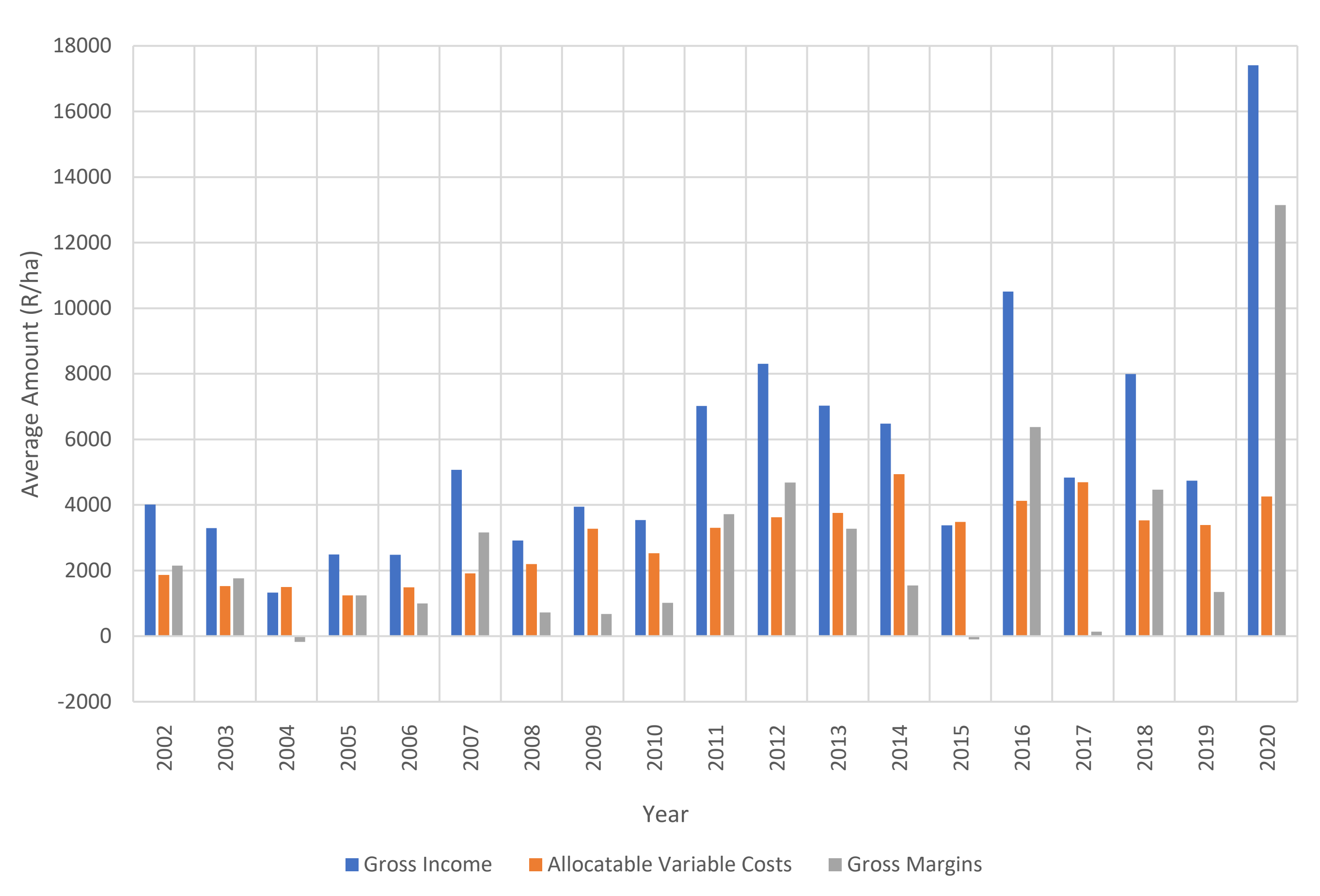


Figure 5.7 - The annual average gross income, allocatable variable costs and gross margins for canola overall from 2002 - 2020.

The average GI for canola was below R 4 000/ha (except in 2007) until 2011, after which it increased to above R 7 000/ha for the rest of the trial period, except in 2015, 2017 and 2019 when the average GI was once again below R 6 000/ha (Figure 5.7). One of the reasons for the increase seen in average annual GIs after 2011, was the availability of new and improved canola cultivars which often brought in higher yields. The highest average GI was in 2020, whilst 2004 had the lowest average GI over the 19-year period. The low average GIs seen in 2004, 2015, 2017 and 2019 could be attributed to lower average canola yields in these years due to drought. The low average GI in 2015 was due to the very low yields that year, since only the canola from the cash cropping systems was harvested. Canola from the other two sub-systems was severely damaged by strong winds and could not be harvested.

The average AVCs of canola remained below R 2 000/ha from 2002 until 2008, after which they increased to between R 2 000/ha and R 4 000/ha for the rest of the trial period, except in 2014, 2017 and 2020, when the average AVCs were above R 4 000/ha. The highest average AVC was recorded in 2014 and the lowest was in 2005.

The average GM for canola was close to R 2 000/ha from 2002-2010, after which it increased to close to R 4 000/ha until 2014 when it dropped again. The exceptions were in 2016, 2018 and 2020 when higher average GMs were seen. There was a negative average GM in 2004 and 2015 and the GM in 2017 was also very low. The low average GMs in 2004 and 2017 may in part be due to lower yields in these years because of low growing season rainfall, as well as the higher average AVCs in these years. The negative average GM in 2015 was due to the very low canola yields that year, since only some camps could be harvested after the severe winds that season. The lower average GMs obtained in the earlier years of the trial may also be attributed to the use of TT cultivars which are associated with lower yields. However, as the trial went on, improved TT cultivars became available which did not have such a limiting effect on yields. The highest average GM was in 2020 and the lowest was in 2004.

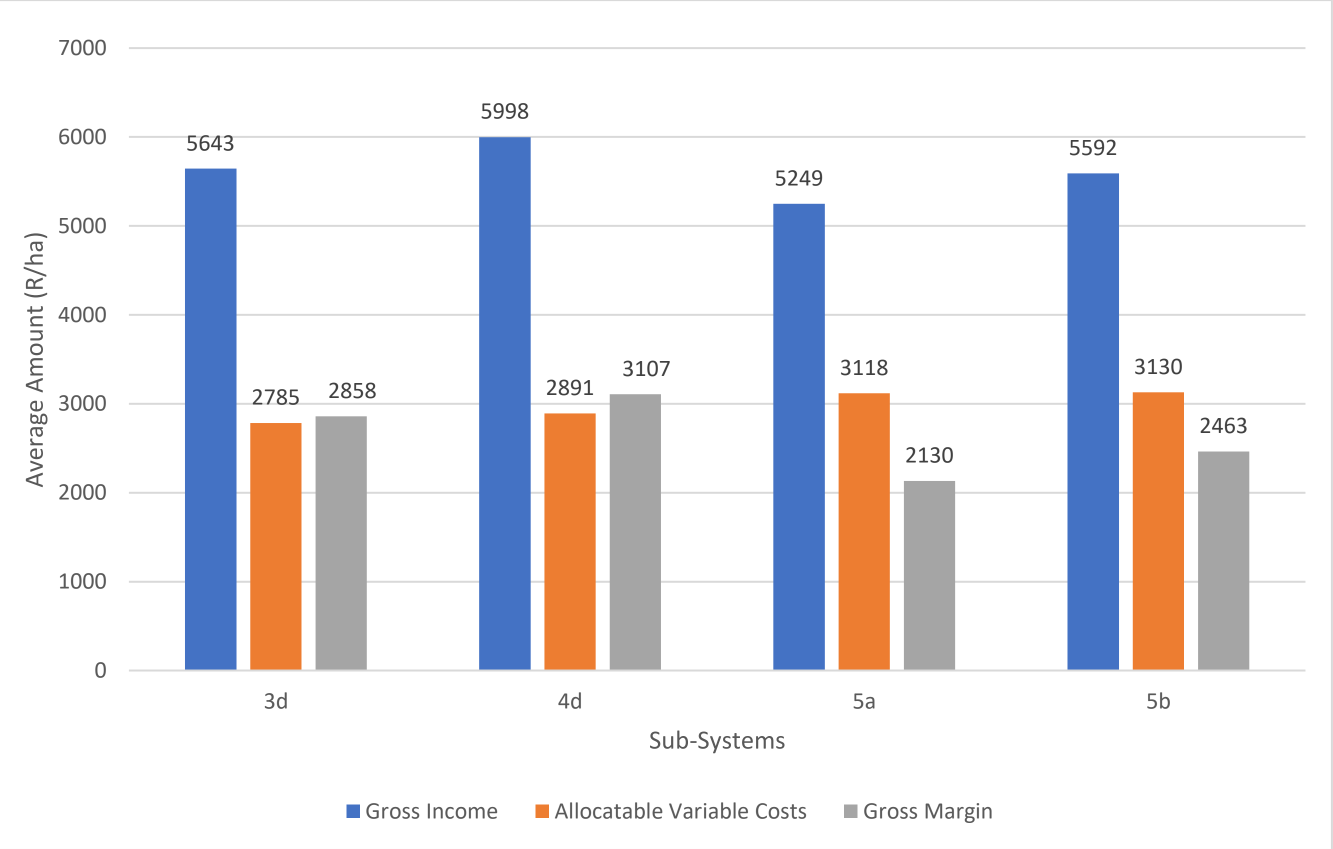


Figure 5.8 - The overall average gross income, allocatable variable costs and gross margins for canola from different sub-systems over a 19-year period from 2002 - 2020.

The overall average GI for all four canola sub-systems was above R 5 000/ha, as illustrated in Figure 5.8. Sub-system 4d (PPCW) had the highest average GI, whilst 5a (WCWL) had the lowest. In sub-system 4d (PPCW), canola followed on two consecutive pasture years, both of which would have increased the soil nitrogen levels which increased the canola yields from this sub-system. Sub-system 5a (WCWL) had one repetition planted on poor-quality soil (camp 11), which lowered yields considerably, thereby lowering the average GI for the sub-system.

The average AVCs for sub-systems 3d (PWPC) and 4d PPCW) were below R 3 000/ha, with 3d being the lowest. Sub-systems 5a (WCWL) and 5b (WBCWBL) both had average AVCs that were above R 3 000/ha, with those for 5b being only marginally higher than for 5a. The average AVCs for all sub-systems were very similar, with only a R 345/ha difference between the highest and lowest average AVC.

The overall average GM for sub-systems 3d (PWPC), 5a (WCWL) and 5b (WBCWBL) were all below R 3 000/ha, with 5a being the lowest. The low average GM for sub-system 5a was linked to the lower average GI for this sub-system which was caused by the lower canola yields from this sub-system. Sub-system 4d (PPCW) had the highest average GM, which was just above R 3 000/ha, probably due to the high average GI for 4d, as this sub-system had higher canola yields, on average, in comparison with other sub-systems (see Figure 4.25).

5.3) Input Costs

There are nine major input costs that were recorded for all camps each year, namely fertiliser, weed control, pest control, fungicide, fuel, lime, seed, contractors and repairs and maintenance. The total input cost was also calculated and recorded. Lime was very seldom used and if so, in small quantities, so it is the lowest input cost for all crops and sub-systems. For pasture systems, the input costs for fungicide, seed, fuel and repairs and maintenance were negligible. Seed costs however, varied for the medic/clover pastures as particular camps needed to be re-established in some years.

5.3.1) Input costs for all sub-systems

5.3.1.1) Input costs for all sub-systems over a 19-year period

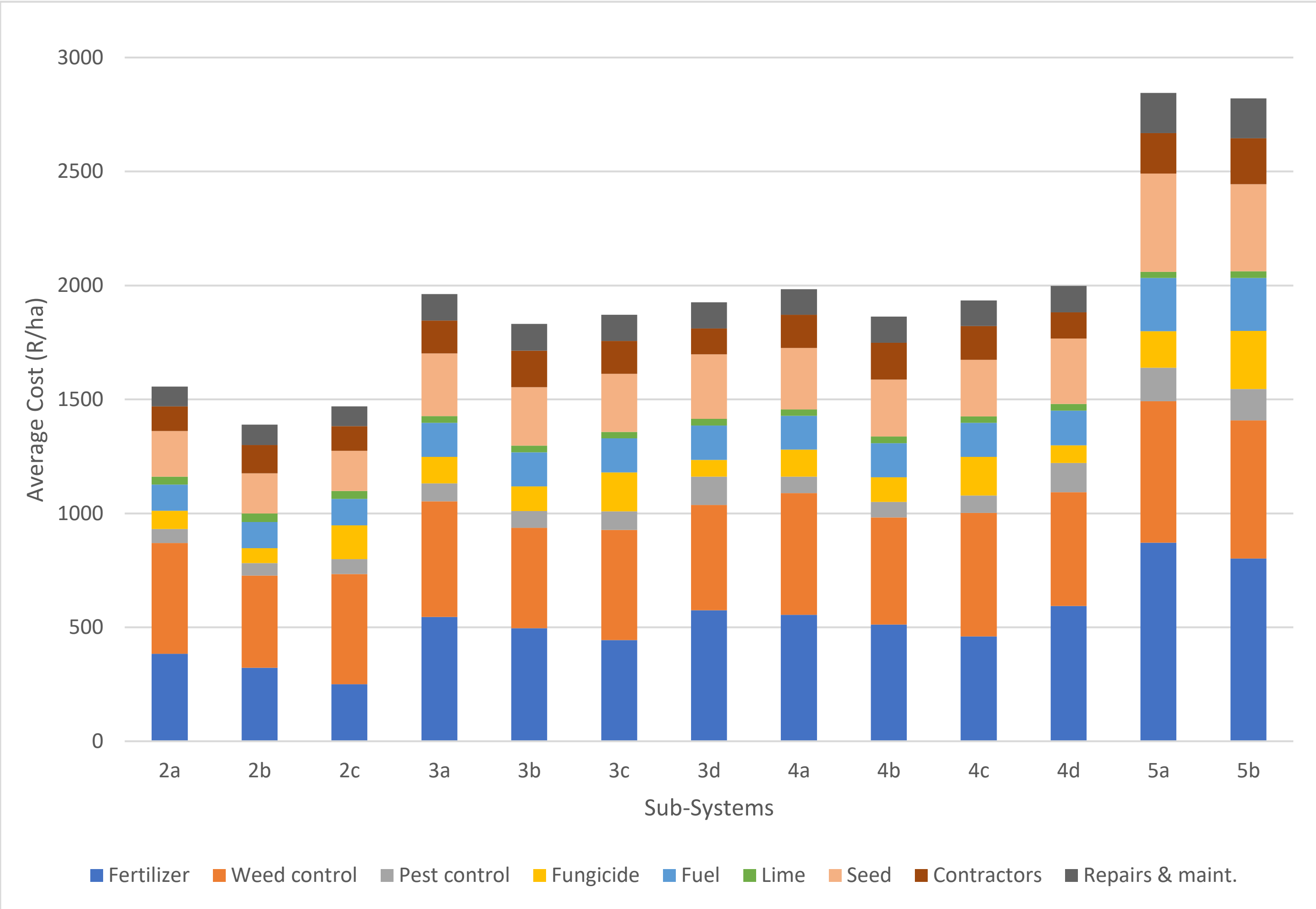


Figure 5.9 - Overall average input costs (per input) for each sub-system as a whole over a 19-year period from 2002 - 2020.

As seen in Figure 5.9, sub-systems 5a (WCWL) and 5b (WBCWBL) had far a higher average total input cost over time than the other sub-systems, with 5a having an average total input cost of R 2 845/ha and 5b being R 2 821/ha. System 5 only had continuous cash cropping sub-systems which are known to often experience weed, pest and disease problems (Hobbs *et al.*, 2008), often requiring higher inputs to manage these problems. One repetition of sub-system 5a (WCWL), was also planted in camp 11 which had poorer soil quality than other camps and had more pest, disease and weed problems relative to other camps. This increased the average total input cost of sub-system 5a. Seed costs were also generally higher for system 5, as the cash crops needed to be sowed annually. Pastures do not need to be sowed annually, which lowered the total input cost for sub-systems containing a pasture element. The average fertiliser cost for system 5 was also higher than those for other systems, due to the omission of pastures in these rotations, leading to lower soil nitrogen and an increased need for mineral fertilisers.

All sub-systems in system 2 had a lower average total input cost than other sub-systems (those in systems 3, 4 and 5). Sub-system 2b (PPO) had the lowest average total input cost at R 1 389/ha, followed by 2c (PPB) and 2a (PPW). Sub-systems in system 3 and 4 had similar average total input costs. The lower average total input cost for system 2 could be attributed to the system only having three-year sequences, which all had two pasture years and one cash cropping year. Pasture years generally have lower average input costs than cash crops as they usually have lower fertiliser, disease control and seed input costs. This lowered the overall average total input cost for system 2, as pastures accounted for 67% of each sub-system from system 2. Systems 3 and 4 were all four-year sequences with two pasture years and two cash cropping years. This led to a higher overall average total input cost, since the cash cropping years made up a larger proportion of each sub-system from these systems. In the initial years of the trial, when minimum tillage was first introduced, there may have been an increase in weed, pest and disease prevalence as is often seen in the early years of CA adoption (Jat *et al.*, 2012). This might have increased the input costs for weed, pest and disease control in the earlier years, but these problems should have stabilised as the trial went on and the benefits of CA started to be realised.

The three inputs that contributed the most to the total input cost for all sub-systems were fertiliser, weed control and seed.

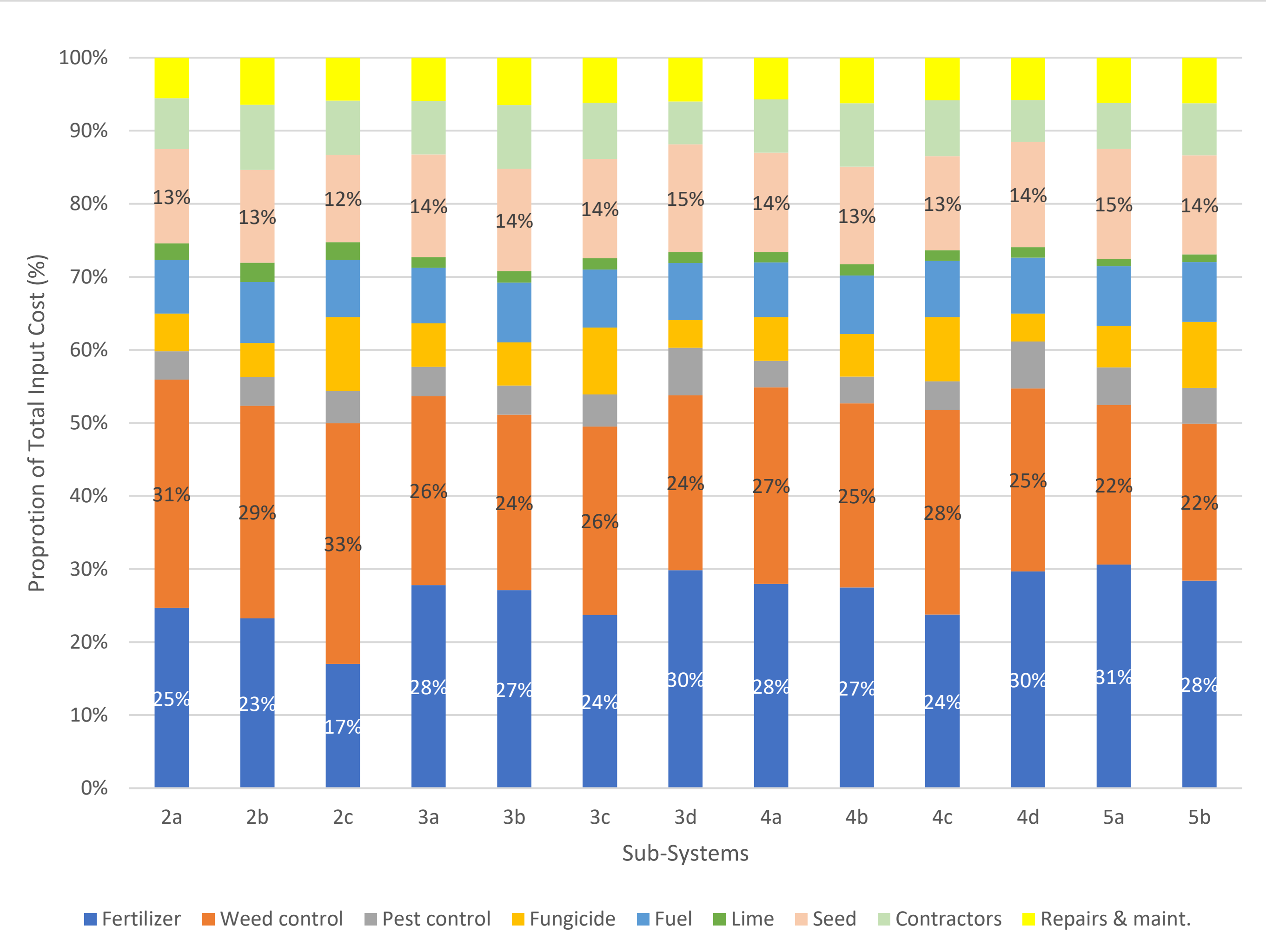


Figure 5.10 - The proportional cost of individual inputs relative to the total input cost for each sub-system over a 19-year period from 2002 - 2020.

The proportional cost of individual inputs relative to the total input cost for all sub-systems is shown in Figure 5.10. Weed control was largest contributor to the total input cost for sub-systems 2a (PPW), 2b (PPO), 2c (PPB), 3c (PWPB) and 4c (PPWB), followed by fertiliser, the second largest contributor. All the above-mentioned sub-systems had two pasture years where weed control was usually the highest input cost as less fertiliser was needed during the pasture years, due to the nitrogen fixation of the leguminous pastures. As mentioned before, sub-systems from system 2 were made up of 67% pastures and 33% cash crops, making the input costs for the pastures more dominant. This could be why weed control makes up the largest proportion of the total input cost for these sub-systems as it’s the most prominent input cost during pasture years.

For all other sub-systems, fertiliser was the biggest contributor to the total input cost, followed by weed control. All the sub-systems from systems 3 and 4 contained 50% pastures and 50% cash crops, which generally required higher levels of fertiliser than sub-systems with only one cash cropping year. Sub-systems from system 5 were made up of 100% cash crops which also required higher levels of fertiliser. Together, fertiliser and weed control made up 50% or more of the total input cost for all sub-systems.

Seed was the third largest contributor to the total input cost for all sub-systems. The relative proportion of other inputs were similar across all the sub-systems, with fuel and contractors commonly being the fourth and fifth largest contributors to the total input cost.

5.3.1.2) Average annual total input cost for each sub-system

Sub-systems 5a (WCWL) and 5b (WBCWBL) consistently had higher average total input costs than all the other sub-systems (Figure 5.11). This could be attributed to the higher average input costs associated with pure cash cropping systems. Sub-systems 2a (PPW), 2b (PPO) and 2c (PPB) consistently had lower total input costs than other sub-systems, but were comparable to the trends of the other sub-systems. System 2 had a 67:33 pasture cash crop ratio which decreased the average total input cost due to the lower input costs associated with pastures in comparison to cash crops.

Over the total period, sub-system 2b (PPO) had the lowest average total input costs, whilst 5a (WCWL) had the highest. The lower average total input cost for sub-system 2b (PPO) could be attributed to the lower average input costs for the pasture years and the lower average input cost for oats when compared to other cash crops. In the first few years of the trial, oats were used for haymaking, which didn’t require very high input levels. From 2008 onwards, oats were produced for the cereal market, where the quality requirements are slightly higher, this necessitated slightly higher input levels which increased the input costs for sub-systems including oats. Sub-system 5a (WCWL) had the highest average total input cost over time. This could be explained by the positioning of the camps for system 5a within the trial layout. As mentioned before, one repetition of 5a fell on camp 11 which had self-compacting soil that resulted in increased stress during the plant growth and development stages which reduced the efficacy of herbicide applications. This camp also had increased pesticide and fungicide requirements in some years which increased the average total input cost considerably.

The cost of inputs over time showed a steady rise in general, as product prices increased. The total input cost for sub-systems from systems 2, 3 and 4 rose steadily until 2015, after which they declined slightly. This may be due to the systems stabilising over time, with the purported benefits of a CA management system becoming more evident, such as a reduced need for fertiliser and weed control due to an overall improvement in soil quality (see Chapter 2.4.4). The act of no-tillage also decreased fuel and machinery costs as farm traffic was reduced (Strauss, 2021). System 5 showed a constant rise in average total input cost over the entirety of the trial.

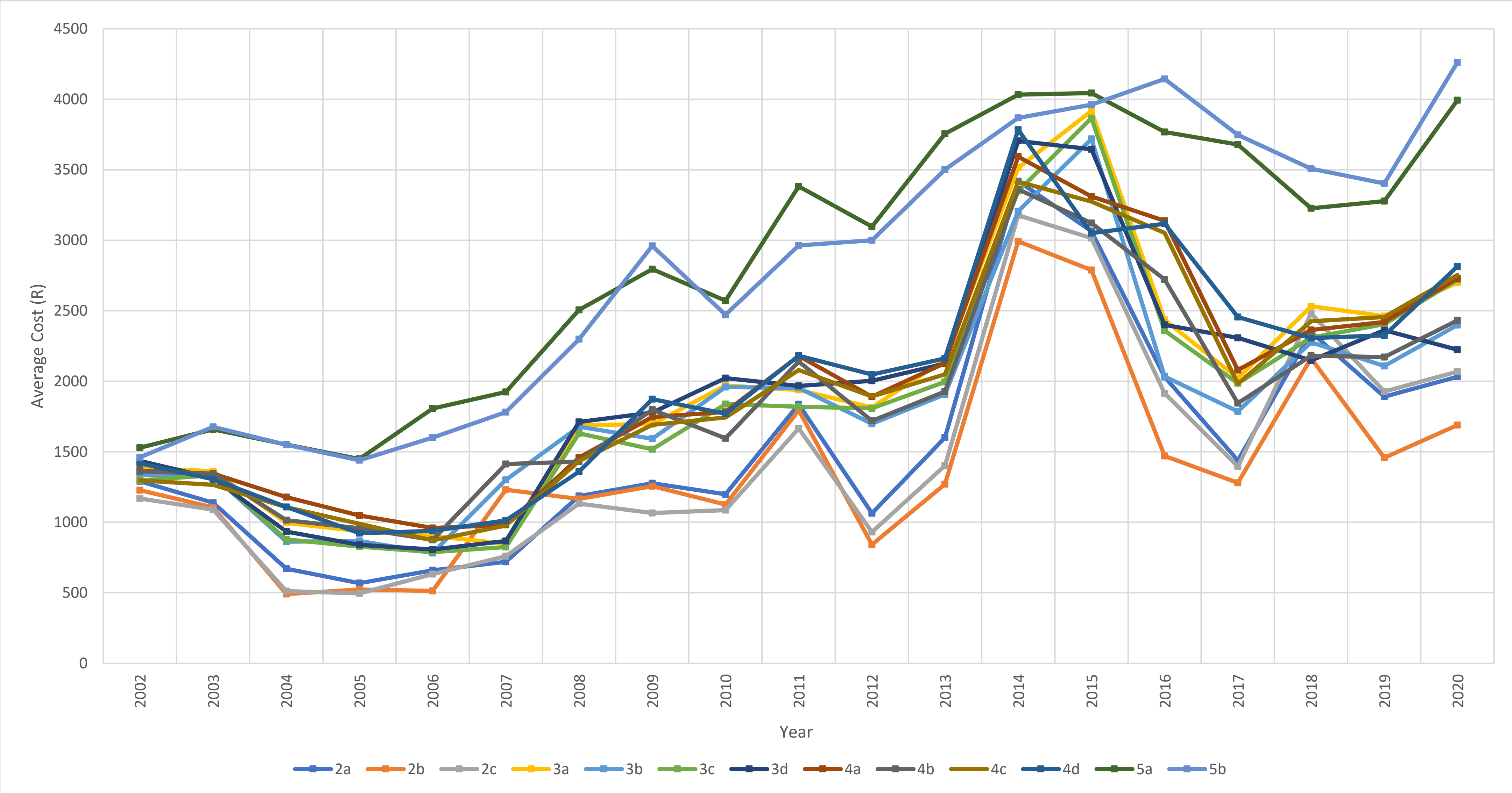


Figure 5.11 - Average annual total input cost for each sub-system from 2002-2020

5.3.2) Input Cost Data for Different Crops Over Time

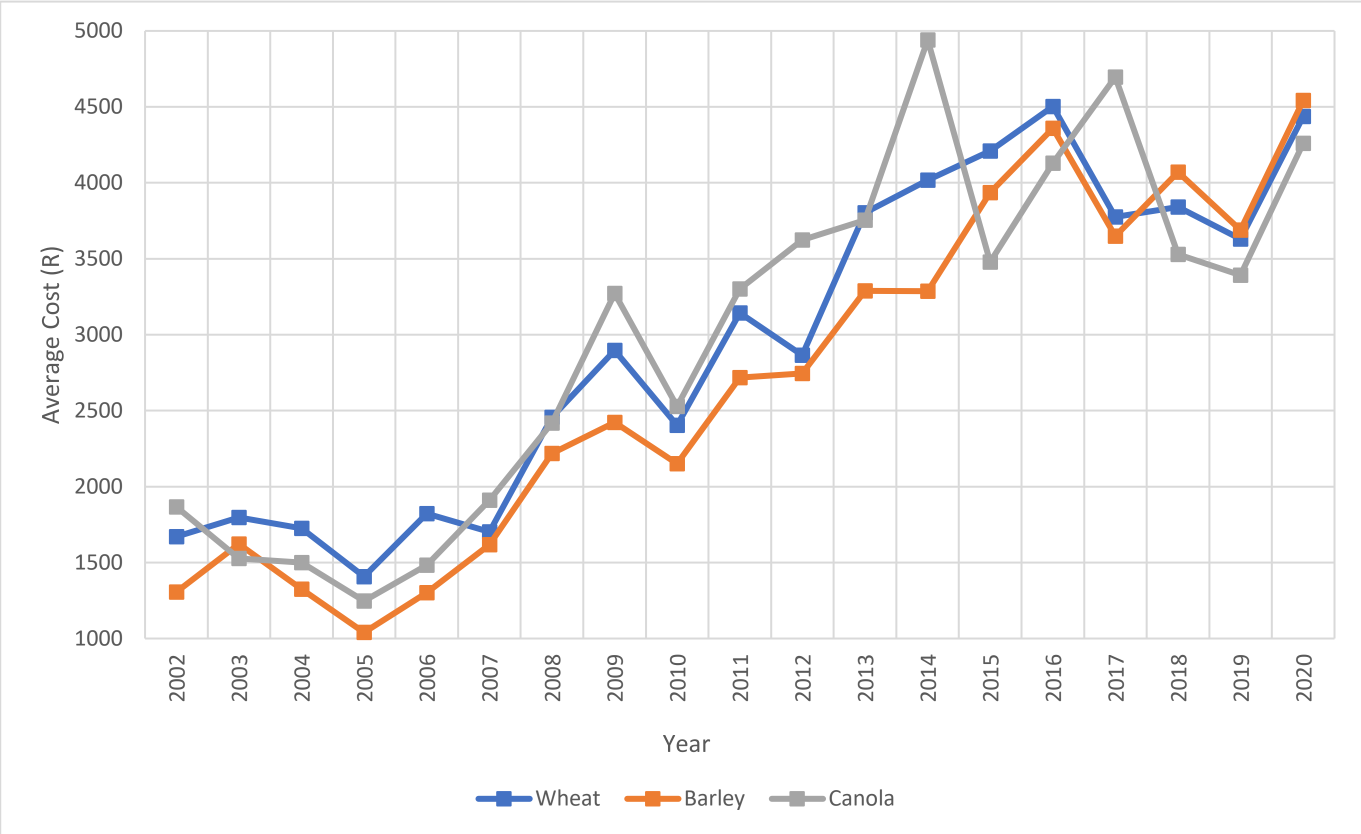


Figure 5.12 - The average annual total input cost for wheat, barley and canola from 2002-2020.

The average annual total input cost for all wheat/barley/canola camps combined each year, regardless of systems, is depicted in Figure 5.12. The average annual total input cost for all three crops increased steadily over the years, with comparable trends until 2014, when the total input cost for canola spiked above those for wheat and barley. This happened again in 2017, when the average total input cost decreased for wheat and barley but increased for canola. The average total input cost for barley was lower than for wheat until 2017, after which the total input cost for canola was lowest for the rest of the trial period. Average total input costs for all crops were lowest in 2005. They were highest for wheat in 2016, barley in 2020 and canola in 2014.

The general overall increase in average total input cost over time, for all crops, could be attributed to price increases for individual inputs over time. The annual total input costs increased steadily until around 2016 when they evened out as the systems became more stable and established. The three spikes in the average total input cost for canola in 2009, 2014 and 2017 may have been due to differences in cultivar choice, for example, choosing a cultivar that might have struggled more with weed and pest competition. In 2014, the average cost of fertiliser for canola systems was very high, as was the cost of fungicide and pest control, relative to the years before that. This increased the total average input cost for canola that year. The increase in total input cost for all crops in 2020 was in part due to an increase in the price of inputs.

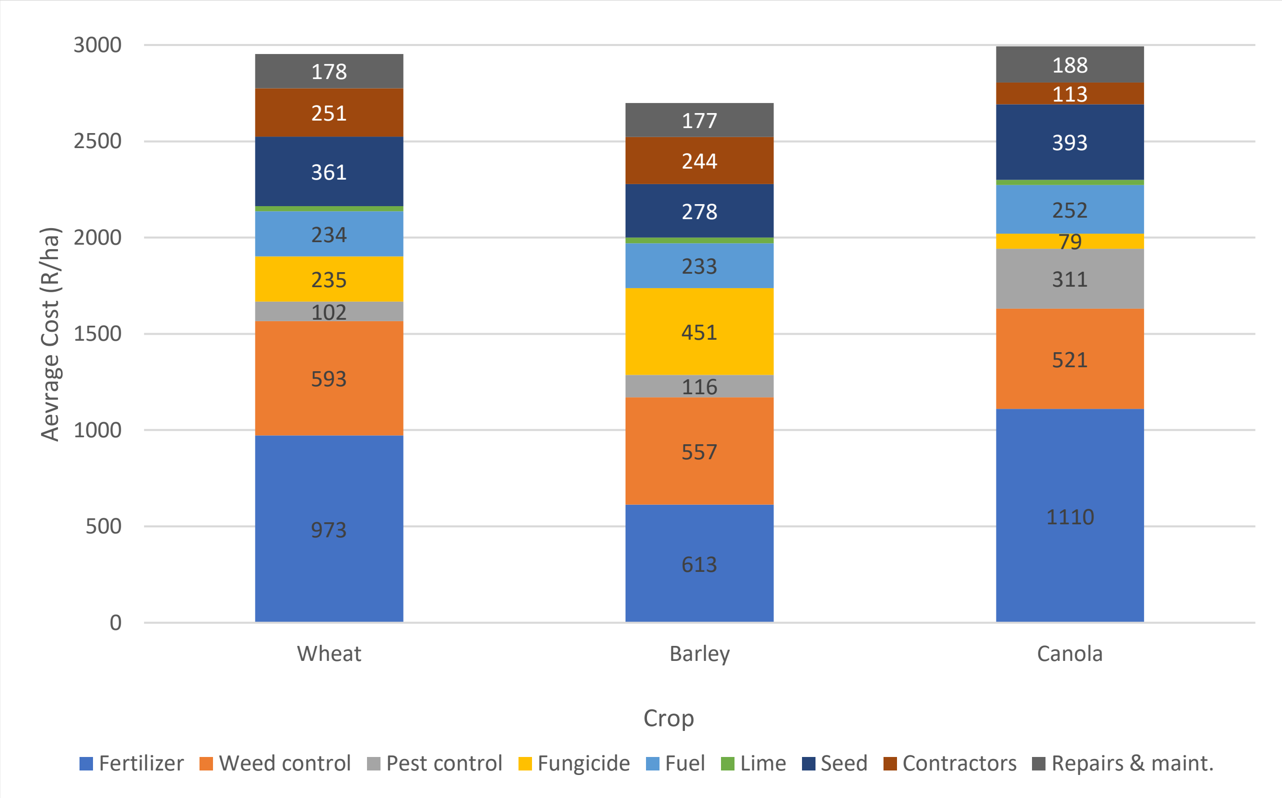


Figure 5.13 - Overall average cost of different inputs for wheat, barley and canola over a 19-year period from 2002 – 2020.

Canola had the highest overall average total input cost over the 19-year trial period, followed by wheat and then barley (Figure 5.13). Fertiliser was the largest input cost for all three crops, with canola having had the highest average fertiliser cost. The second highest input cost for all three crops is weed control, with wheat having had the highest average cost for weed control, followed by barley and canola. The third highest input cost for both wheat and canola was seed, whilst for barley it was fungicide. The initial fungicide costs for barley may have been high, but over time, better cultivars became available which were more resistant to disease which lowered the spraying costs as the trial went on. The cost of seed is the highest for canola, followed by wheat and then barley. The seeding rate of barley was lower than that of wheat and canola which reduced the average seed costs for barley. The cost of pest control is very low for both wheat and barley but is the fourth highest input cost for canola. Canola often requires more comprehensive pest control – slug pellets and insecticides were used at the start of the season to protect the small plants and then, as the crop matured, diamondback moths often become an issue and need to be controlled (Strauss, 2021). This raised the pest control costs for canola.

5.3.2.1) Wheat Input Costs

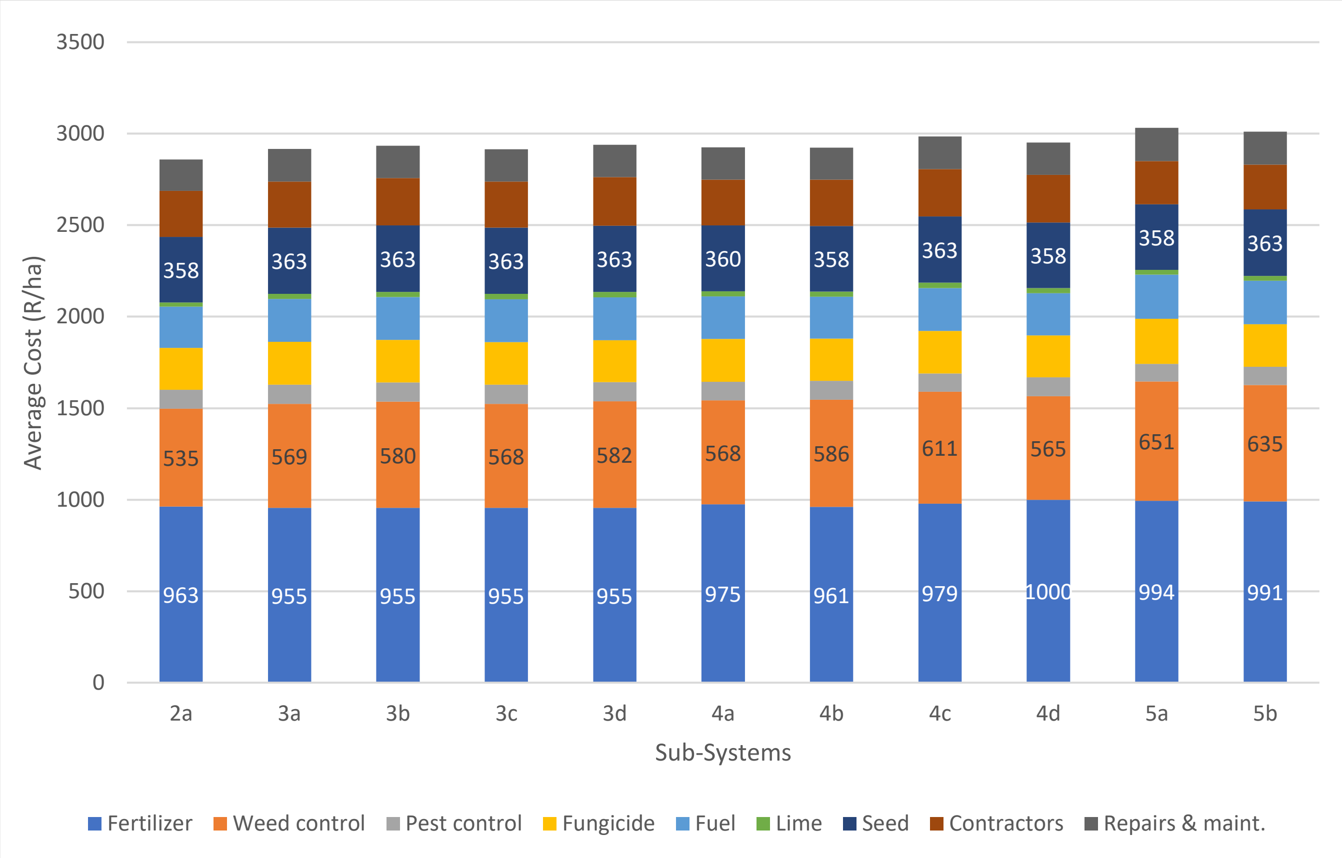


Figure 5.14 - Overall average cost of different inputs for wheat from different sub-systems over a 19-year period from 2002-2020.

The overall average costs of different inputs for different wheat sub-systems over the entire 19-year period of the trial is reflected in Figure 5.14. The majority of wheat sub-systems had a total average input cost that was above R 2 500/ha and just below R 3 000/ha. Only sub-systems 5a (WCWL) and 5b (WBCWBL) had an average total input cost above R 3 000/ha. The sub-systems with the lowest total average input costs were 2a (PPW), 3c (PWPB) and 3a (PWPW) respectively. Those with the highest total average input costs are 5a (WCWL), 5b (WBCWBL) and 4c (PPWB) respectively. Fertiliser was the largest input cost for all wheat sub-systems, followed by weed control and seed. The sub-systems with the highest fertiliser costs were 4d (PPCW), 5a (WCWL) and 5b (WBCWBL) respectively. The sub-systems with the highest weed control costs were 5a (WCWL), 5b (WBCWBL) and 4c (PPWB) respectively. The seed costs for all the sub-systems were very similar and ranged between R 358/ha and R 364/ha. The slightly higher weed control and fertiliser costs seen for sub-systems 5a (WCWL) and 5b (WBCWBL) might have been due to the omission of pastures in these sub-systems. Therefore, these sub-systems did not have the benefit of added soil nitrogen from the leguminous pasture years and also could not use the pasture years as a chance to break weed, disease and pest cycles. This increased the need for both fertiliser and weed control in these sub-systems. The poor soil type in one repetition of sub-system 5a (camp 11) might have also increased input costs.

5.3.2.2) Barley Input Costs

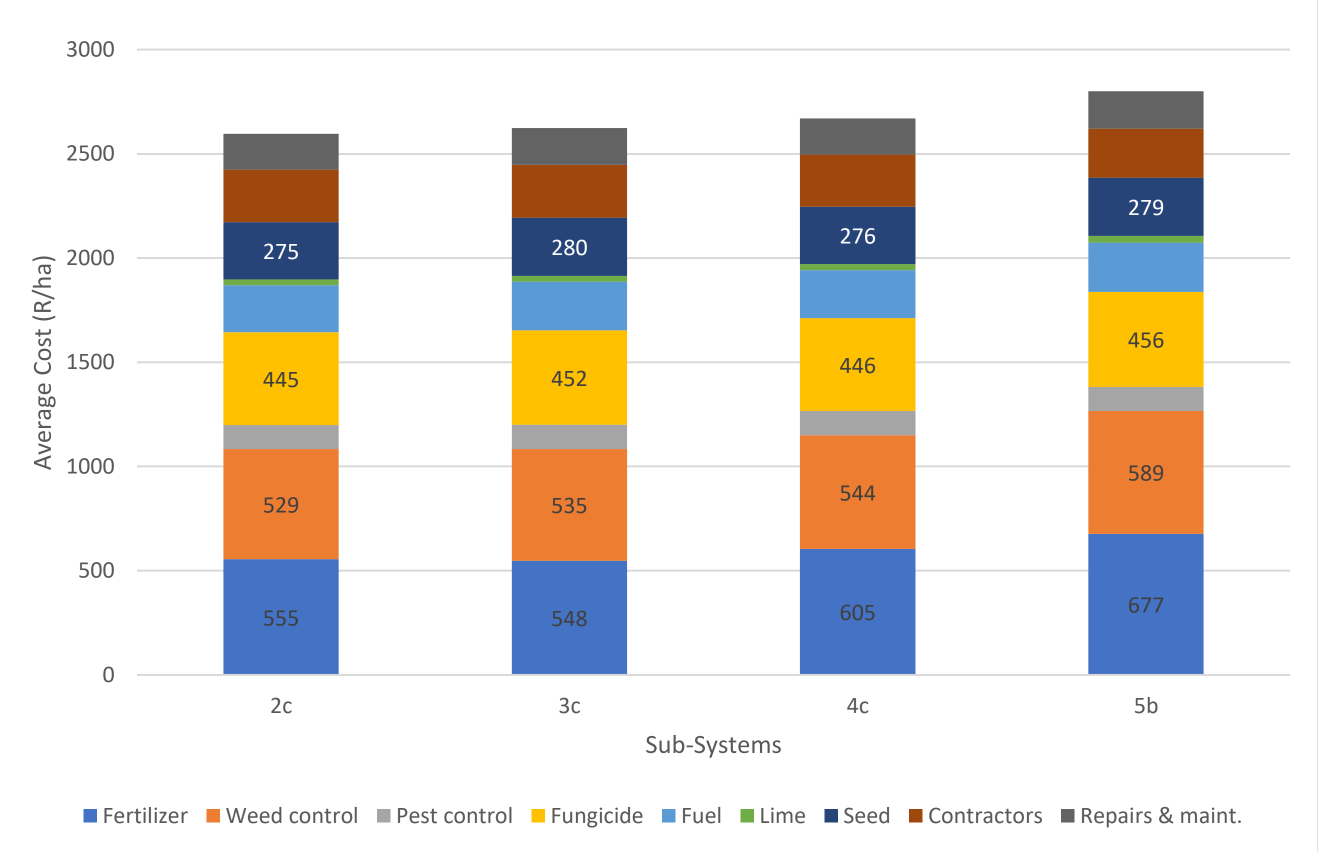


Figure 5.15 - The overall average cost of different inputs for barley from different sub-systems over a 19-year period from 2002-2020.

The average total input cost for barley sub-systems over the entire trial period were all slightly above R 2 500/ha but below R 3 000/ha (Figure 5.15). Sub-system 5b (WBCWBL) had the highest average total input costs, followed by 4c (PPWB), 3c (PWPB) and 2c (PPB), respectively. Sub-systems 4c (PPWB), 3c (PWPB) and 2c (PPB) had very similar average total input costs, between R 2 595/ha and R 2 670/ha. Fertiliser was the main input cost for all barley sub-systems, followed by weed control which was similar to the cost of fertiliser but slightly lower. The third highest, but similar, input cost for all sub-systems was fungicide. Sub-system 5b (WBCWBL) had the highest average fertiliser, weed control and fungicide input costs. The omission of pastures in sub-system 5b increased the cost for weed control and fertiliser, since these costs were higher for crop years than for pasture years. The barley in sub-system 5b (WBCWBL) also always followed on from a wheat year, making it more susceptible to grass weeds, pests and diseases which were not able to be controlled as effectively in the previous wheat year. Sub-system 4c (PPWB) had the second highest fertiliser and weed control costs whilst 3c (PWPB) had the second highest fungicide costs.

5.3.2.3) *Canola Input Costs*

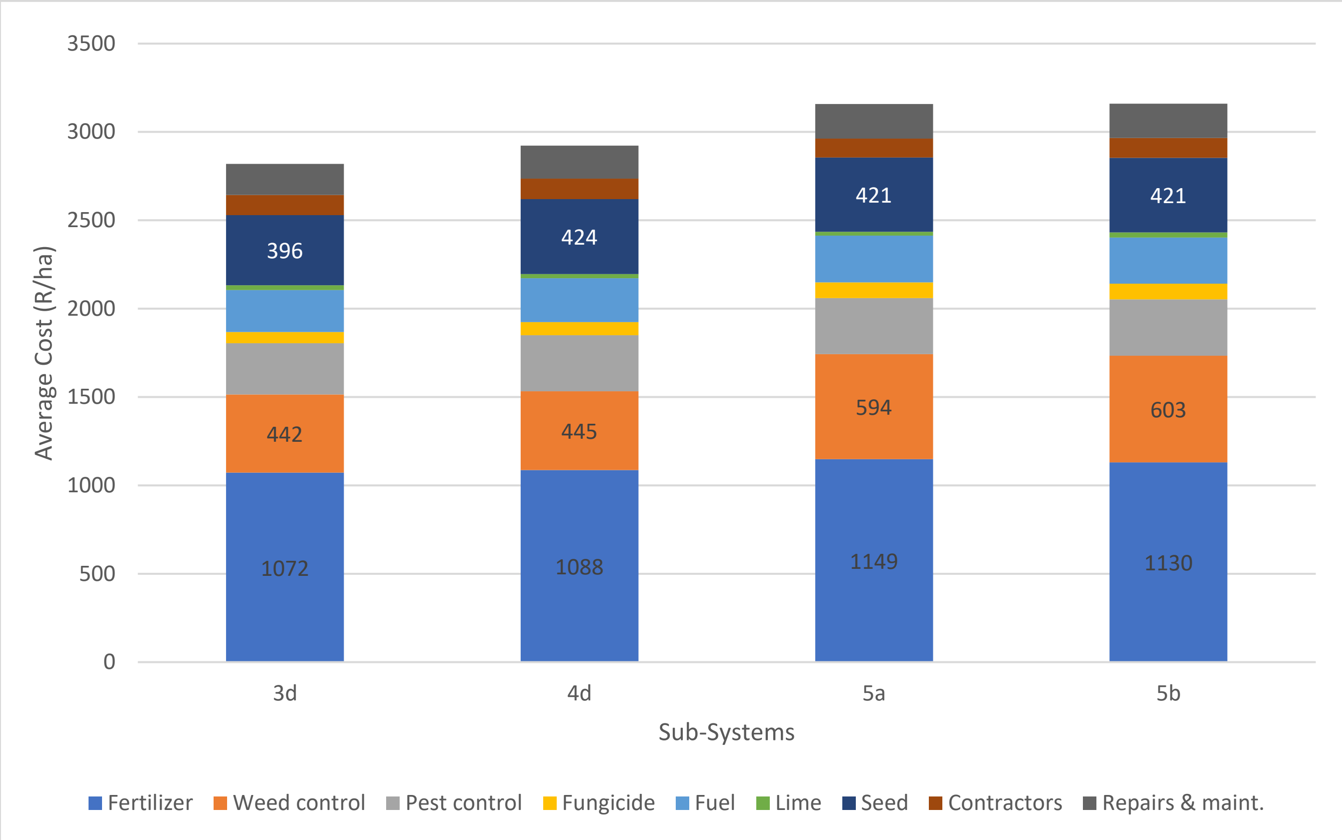


Figure 5.16 - The average costs of different inputs for canola from different sub-systems over a 19-year period from 2002 - 2020.

The average total input cost for different canola sub-systems ranged between R 2 500/ha and R 3 500/ha (Figure 5.16). Sub-systems 5a (WCWL) and 5b (WBCWBL) both had similar average total input costs which were above R 3 000/ha. Sub-systems 3d (PWPC) and 4d (PPCW) both had an average total input cost below R 3 000/ha, with 3d being slightly lower than 4d. Fertiliser was the highest input cost for all sub-systems, followed by weed control and then seed. The average cost of fertiliser and weed control was highest in sub-systems 5a (WCWL) and 5b (WBCWBL). This could have been caused by the omission of pastures in these sub-systems as well as the poorer quality soil for one repetition of sub-system 5a. The cost of seed was similar for all sub-systems.

5.3.3) Analysis of Individual Input Costs per crop over time

5.3.3.1) Fertiliser

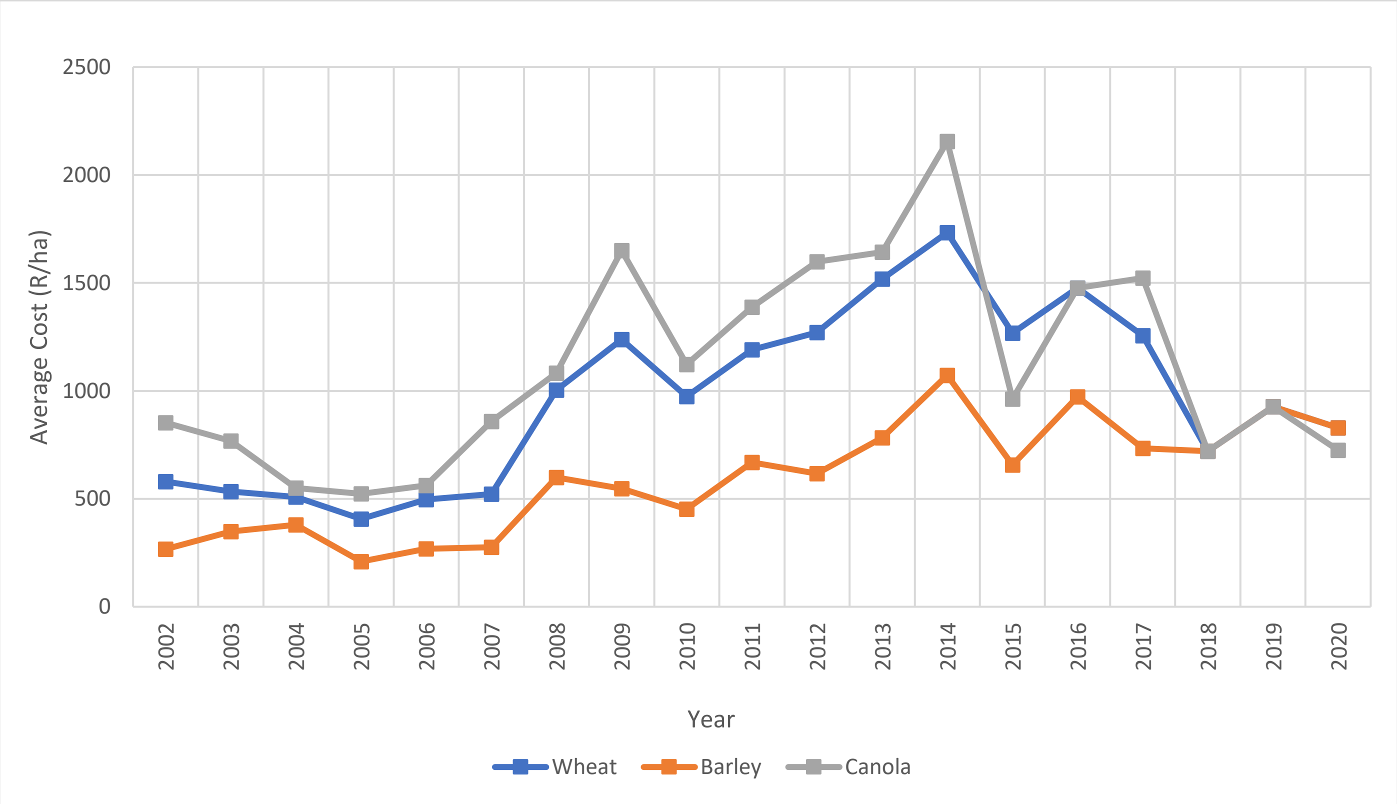


Figure 5.17 - The average annual cost of fertiliser for wheat, barley and canola from 2002 - 2020.

The average cost of fertiliser for each crop was recorded annually from 2002 until 2020 (Figure 5.17). From 2002 until 2014, the average cost of fertiliser in canola systems was the highest, followed by wheat and then barley, all portraying similar trends. In 2015, the average cost of fertiliser in canola systems dropped below that of wheat, but then rose again in 2017. In 2018 and 2019, the average cost of fertiliser for all three crops was the same. The reason for this could be that from 2018 onwards, a disc planter was used which required less fertiliser than the previous tine planter at planting, as using similar amounts as in the case of the tine planter could burn the seed. A very similar fertiliser mix was used for all three crops during the years when a disc planter was used, which might explain the nearly identical fertiliser costs between crops. Topdressings was not increased with the difference in fertiliser between the tine and disc seeders. The average cost of fertiliser for all three crops peaked in 2014 and was at its lowest in 2005. Average fertiliser costs for all crops increased steadily until around 2014, after which they decreased and began to stabilise. This may be the result of CA principles such as no-tillage and crop residue retention. The use of both of these practices in combination is known to increase soil health which in turn increases the nutrients available to crops, reducing the need for mineral fertilisers (Hobbs, 2007). The average cost of fertiliser for barley was consistently lower than that for both wheat and canola since barley requires less nitrogen at planting than wheat and canola.

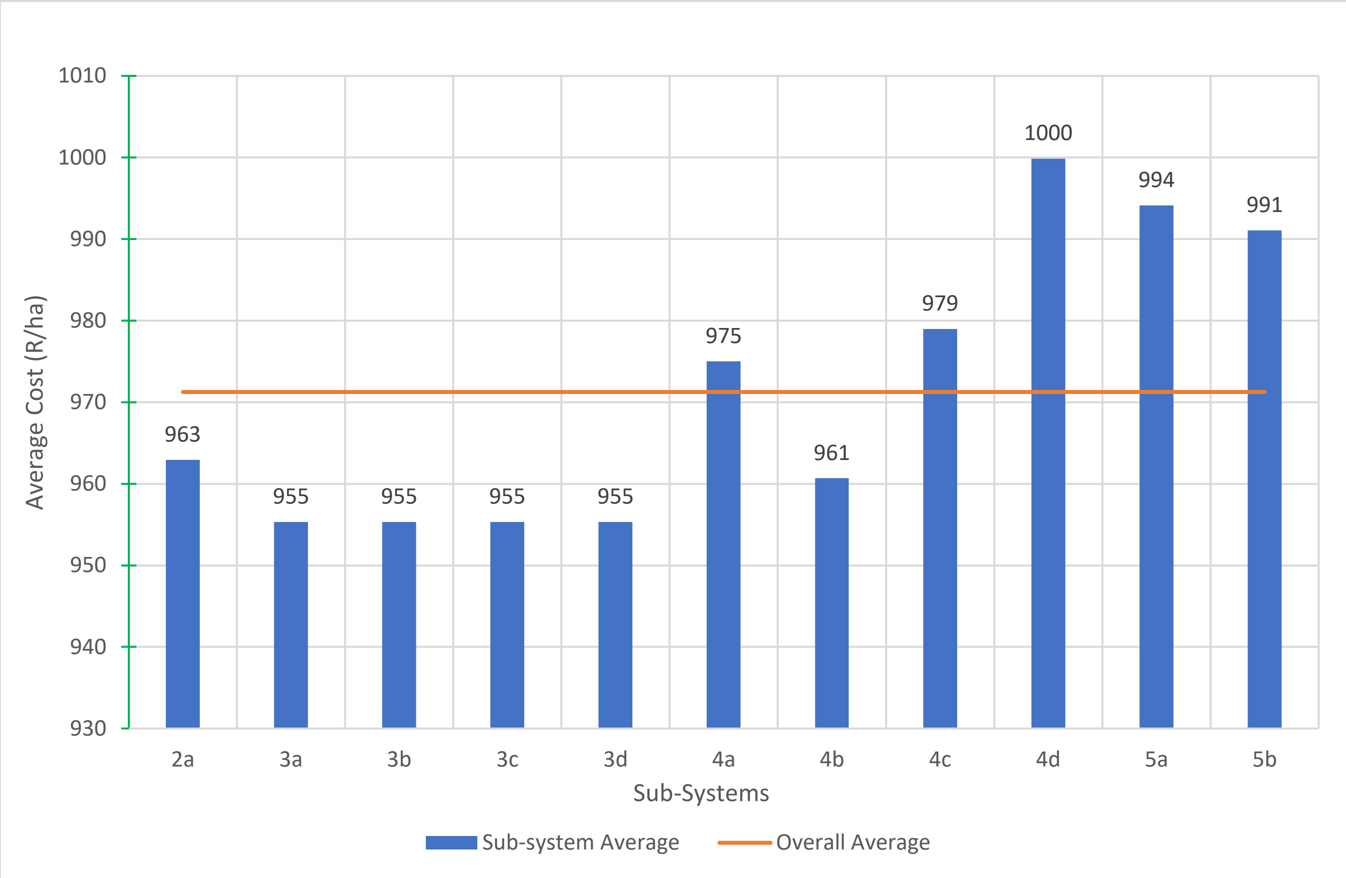


Figure 5.18 - The average cost of fertiliser for wheat from different sub-systems over a 19-year period from 2002 - 2020. The line depicts an overall average cost of all sub-systems tested.

Sub-systems 2a (PPW), 3a (PWPW), 3b (PWPO), 3c (PWPB), 3d (PWPC) and 4b (PPOW) had below average fertiliser costs, whilst sub-systems 4a (PPWW), 4c (PPWB), 4d (PPCW), 5a (WCWL) and 5b (WBCWBL) had above average fertiliser costs (Figure 5.18). The sub-system with the highest average fertiliser cost was 4d (PPCW), followed by 5a (WCWL) and 5b (WBCWBL). The high average fertiliser cost for sub-system 4d (PPCW) could have been due to the choice of canola cultivar for this rotation which may have increased the average fertiliser costs for the sub-system. The higher fertiliser costs for sub-system 5a (WCWL) could be attributed to the one repetition planted in camp 11 which had higher fertiliser needs due to the poor soil quality. Sub-system 5b (WBCWBL) also had higher fertiliser costs and this might have been caused by the omission of pastures in the rotation which often increased the need for fertiliser. All sub-systems from system 3 had equal average fertiliser costs (R 955/ha), which was the lowest average fertiliser cost overall.

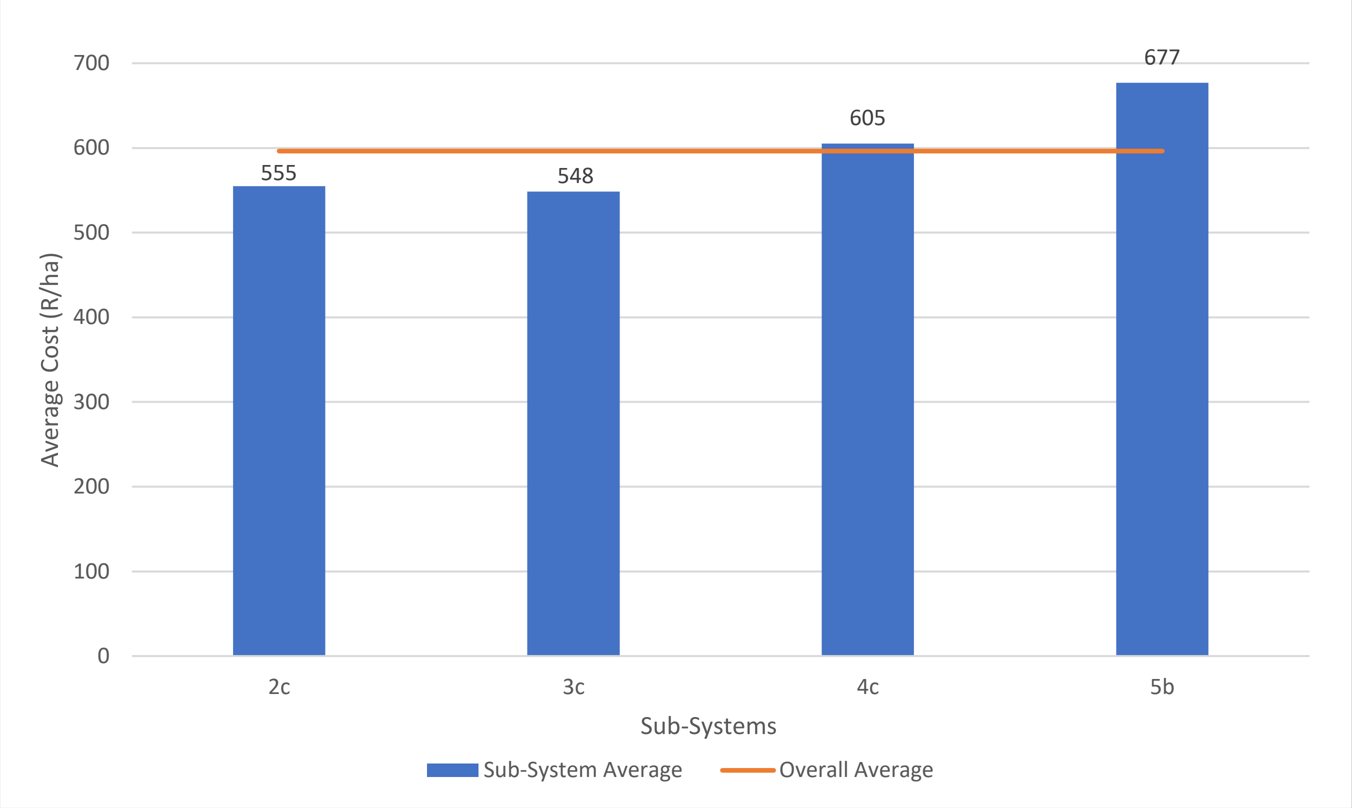


Figure 5.19 - The average cost of fertiliser for barley from different sub-systems over a 19-year period from 2002 - 2020. The line depicts the overall average cost of all sub-systems tested.

The average cost of fertiliser for individual barley sub-systems over the entire trial period, as well as the overall average cost of fertiliser for all sub-systems together (R 596/ha) is depicted in Figure 5.19. The average fertiliser costs of sub-systems 4c (PPWB) and 5b (WBCWBL) were above the overall average, whilst average fertiliser costs for sub-systems 2c (PPB) and 3c (PWPB) were below the overall average. Sub-system 5b (WBCWBL) had the highest average fertiliser cost and sub-system 3c (PWPB) had the lowest average fertiliser cost, followed closely by sub-system 2c (PPB). The lower fertiliser costs for sub-systems 2c (PPB), 3c (PWPB) and 4c (PPWB) could be linked to the incorporation of pastures in these rotation systems which are known to reduce the need for fertiliser, to some extent. Sub-system 5b (WBCWBL) had two barley years, both of which were following wheat. Barley from this sub-system may have had less soil nutrients available, then requiring higher levels of fertiliser.

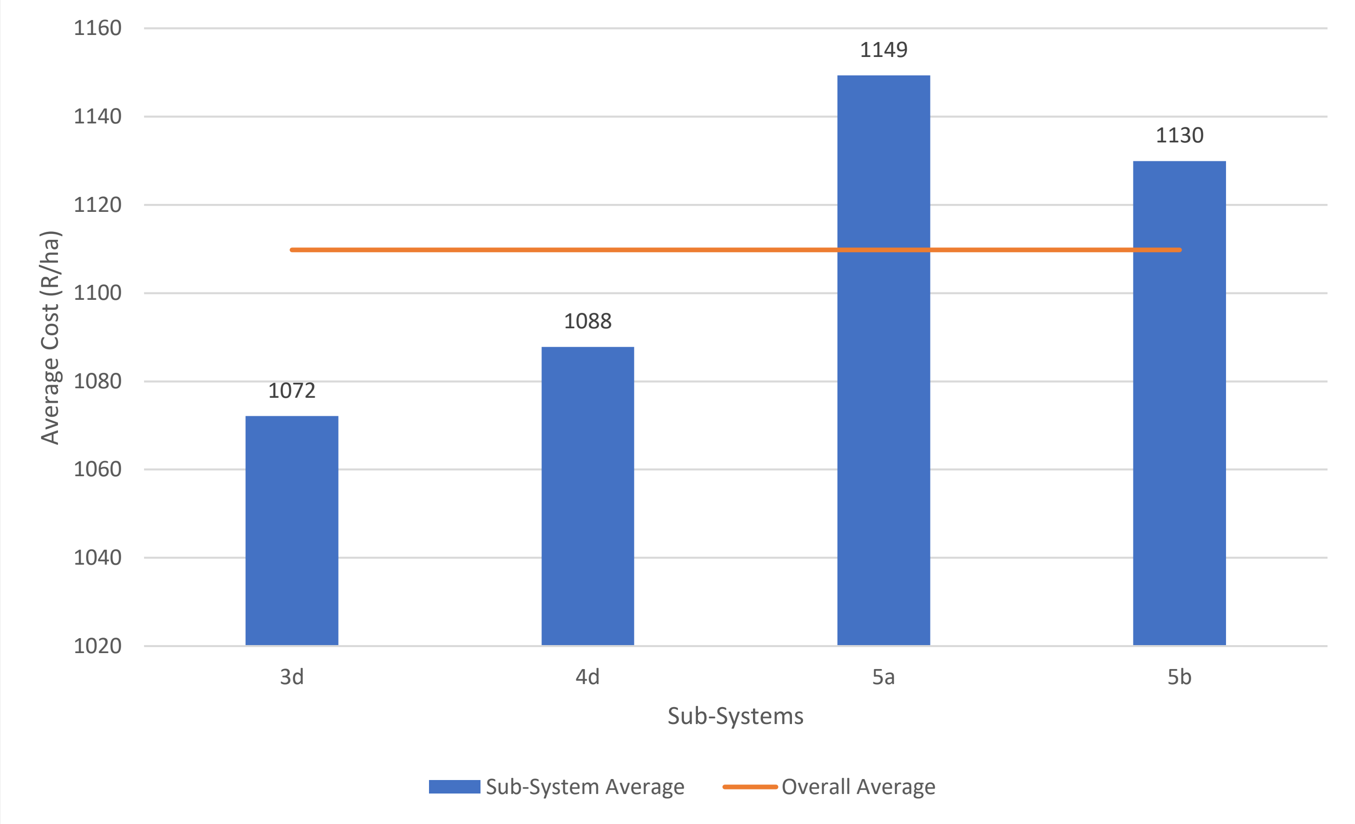


Figure 5.20 - The average cost of fertiliser for canola from different sub-systems over a 19-year period from 2002 - 2020. The line depicts the overall average cost of all sub-systems tested.

The overall average cost of fertiliser for all the sub-systems together was R 1 110/ha (Figure 5.20). The average cost of fertiliser for sub-systems 5a (WCWL) and 5b (WBCWBL) were higher than the overall average, with 5a being the highest. The higher fertiliser costs of sub-system 5a (WCWL) was due to this sub-system having canola present every fourth year whilst sub-system 5b (WBCWBL) only had canola every sixth year. Therefore, sub-system 5a (WCWL) had more canola years over the trial period than sub-system 5b (WBCWBL) and this increased the overall average fertiliser costs for 5a, since canola required more fertiliser than other crops tested.

The average cost of fertiliser for sub-systems 3d (PWPC) and 4d (PPCW) were below the overall average, with 4d having been the lowest. The average fertiliser costs for all sub-systems were between R 1 060/ha and R 1 160/ha. Sub-systems 3d and 4d only had two cash cropping years in the four-year sequence, with two pasture years. The nitrogen-fixation during the pasture years may have lowered the fertilizer requirements for canola in these sub-systems.

5.3.3.2) Weed Control

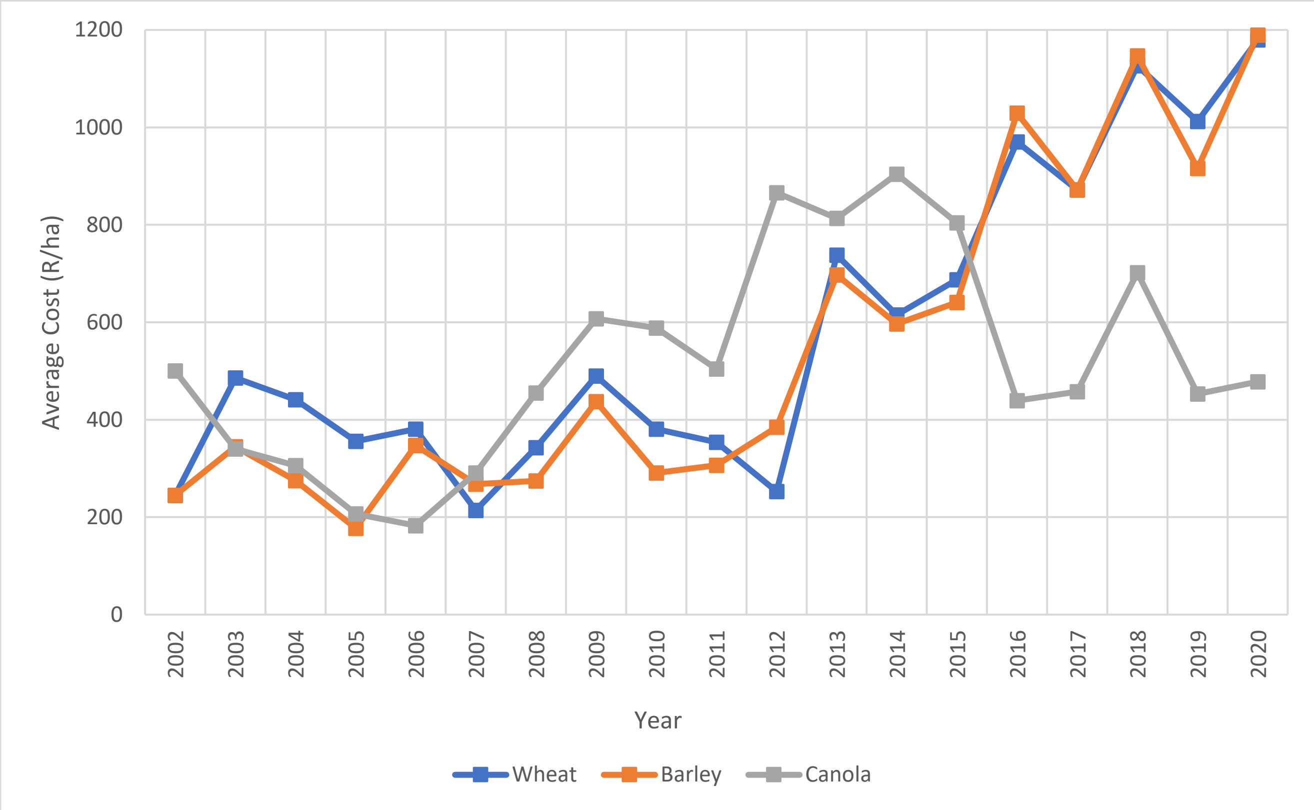


Figure 5.21 - The average annual cost of weed control for wheat, barley and canola from 2002 - 2020.

The average cost of weed control for each crop was recorded annually from 2002 until 2020 (Figure 5.21). The average annual cost of weed control for both wheat and barley followed similar trends over the years, whilst the cost of weed control for canola was more varied. Wheat had the highest average cost of weed control from 2003 – 2006, after which canola had the highest average cost from 2007 – 2015. After 2015, the average cost of weed control in canola systems decreased to below that of wheat and barley and remained so until 2020. The average cost for weed control in the different crops varied over the years (Figure 5.21). The highest average weed control costs for wheat and barley were in 2020, whilst the highest average weed control cost for canola was in 2014. The lowest average weed control cost for barley and canola were in 2005, whilst the lowest cost for wheat was in 2007.

The overall increase in the average cost of weed control for both wheat and barley over time was mainly due to price increases for herbicides. The cultivar choice also had a big impact on the average cost of weed control as some cultivars are more resistant to weeds and need less herbicide than others which may require very specific herbicides. This could have increased the average cost of weed control in some years. A possible explanation for the high average weed control costs for canola from 2007 until 2015 could be the limited number of available herbicides, most of which were more expensive than the bigger choice of herbicides available for barley and wheat. As canola cultivars improved and more herbicides became available, the average cost of weed control for canola decreased.

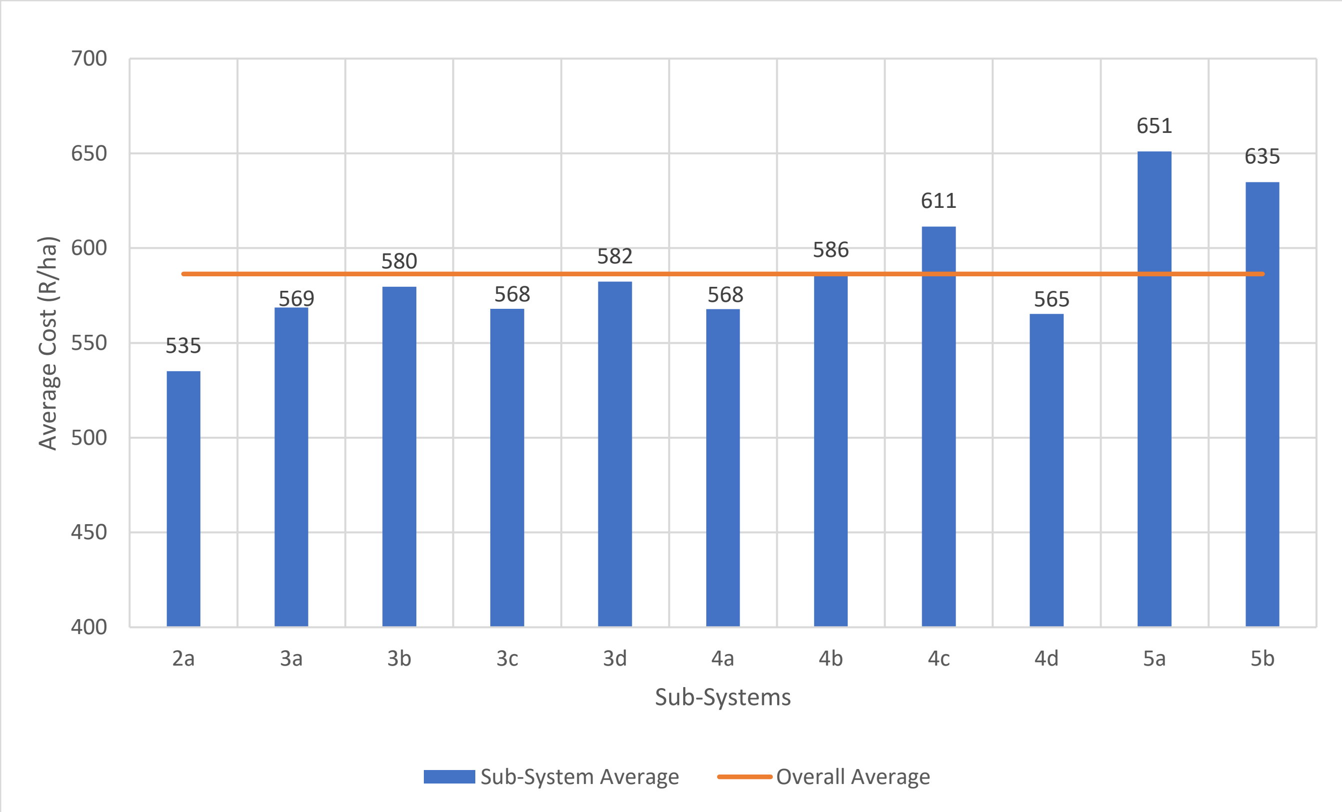


Figure 5.22 - The average cost of weed control for wheat from different sub-systems over a 19-year period from 2002 - 2020. The line depicts the overall average cost of all sub-systems tested.

The overall average cost of weed control for all the sub-systems together was R 586/ha (Figure 5.22). Most of the wheat sub-systems had average weed control costs below the overall average. Only sub-systems 4c (PPWB), 5a (WCWL) and 5b (WBCWBL) had weed control costs that were higher than the overall average cost. Sub-system 5a (WCWL) had the highest average cost, followed by 5b (WBCWBL) and 4c (PPWB). The reasons for the high average weed control costs for sub-system 5a (WCWL) could be attributed to the one repetition planted in camp 11. Plant growth was not as vigorous in camp 11 which resulted in weeds being more prevalent, increasing the competition between weed growth and crop growth which then required more rigorous weed control. There were also no pastures in sub-systems 5a (WCWL) and 5b (WBCWBL), which usually had less weed problems than cash crops, this consequently increased the average cost of weed control up for both sub-systems. Sub-system 4c (PPWB) had barley following directly after wheat which often resulting in grass weed problems. Barley and wheat both have the same physiology as grass weeds, thus grass weeds cannot be controlled as efficiently in either barley or wheat years, only in pasture years.

Sub-system 2a (PPW) had the lowest average cost for weed control, followed by 4d (PPCW) and 4a (PPWW) (Figure 5.22). Sub-system 2a (PPW) was only a three-year sequence, two of which were pasture years with lower weed control costs which lowers the average weed control cost for the sub-system. Sub-system 4d (PPCW) had two pasture years and a canola year before the wheat, allowing for weed cycles to be broken before the wheat year which lowers the average cost of weed control.

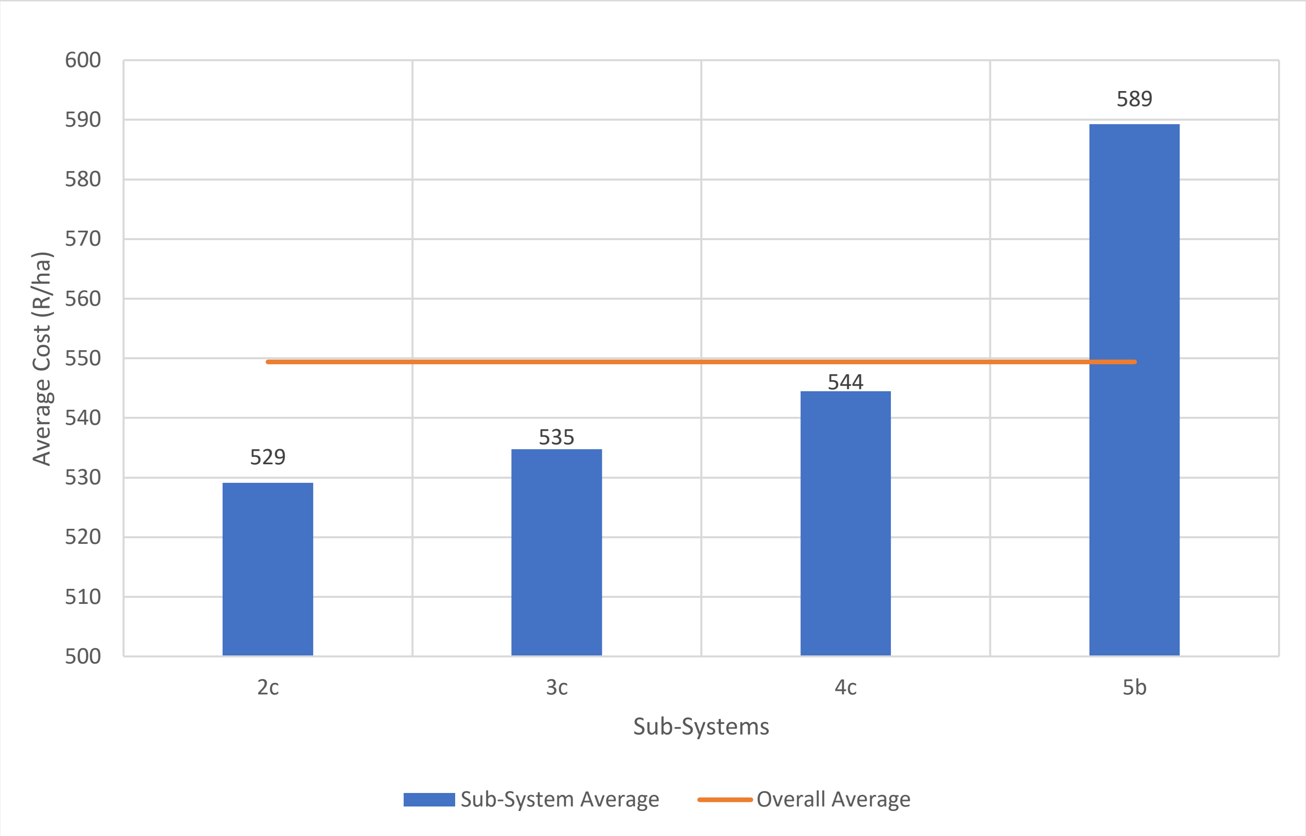


Figure 5.23 - The average cost of weed control for barley from different sub-systems over a 19-year period from 2002 - 2020. The line depicts the overall average cost of all sub-systems tested.

The overall average cost of weed control for all the sub-systems together was R 549/ha (Figure 5.23). The only sub-system with an average weed control cost above the overall average cost was 5b (WBCWBL), whilst sub-systems 2c (PPB), 3c (PWPB) and 4c (PPWB) all had below overall average weed control costs.

One reason for the considerably higher weed control costs for sub-system 5b (WBCWBL) is that there were two barley years in this sub-system, whilst all other sub-systems only had one barley year. Each barley year also had two repetitions, so while barley was planted in four camps for sub-system 5b, it was only planted in two camps for the other sub-systems. The higher number of barley camps increased the variability in weed control needs for the sub-system and increased the average weed control costs for 5b. Barley also always followed wheat for both sub-systems 5b (WBCWBL) and 4c (PPWB) which often leads to problems with grass weeds that needed additional herbicide. This increased the average cost of weed control for these sub-systems.

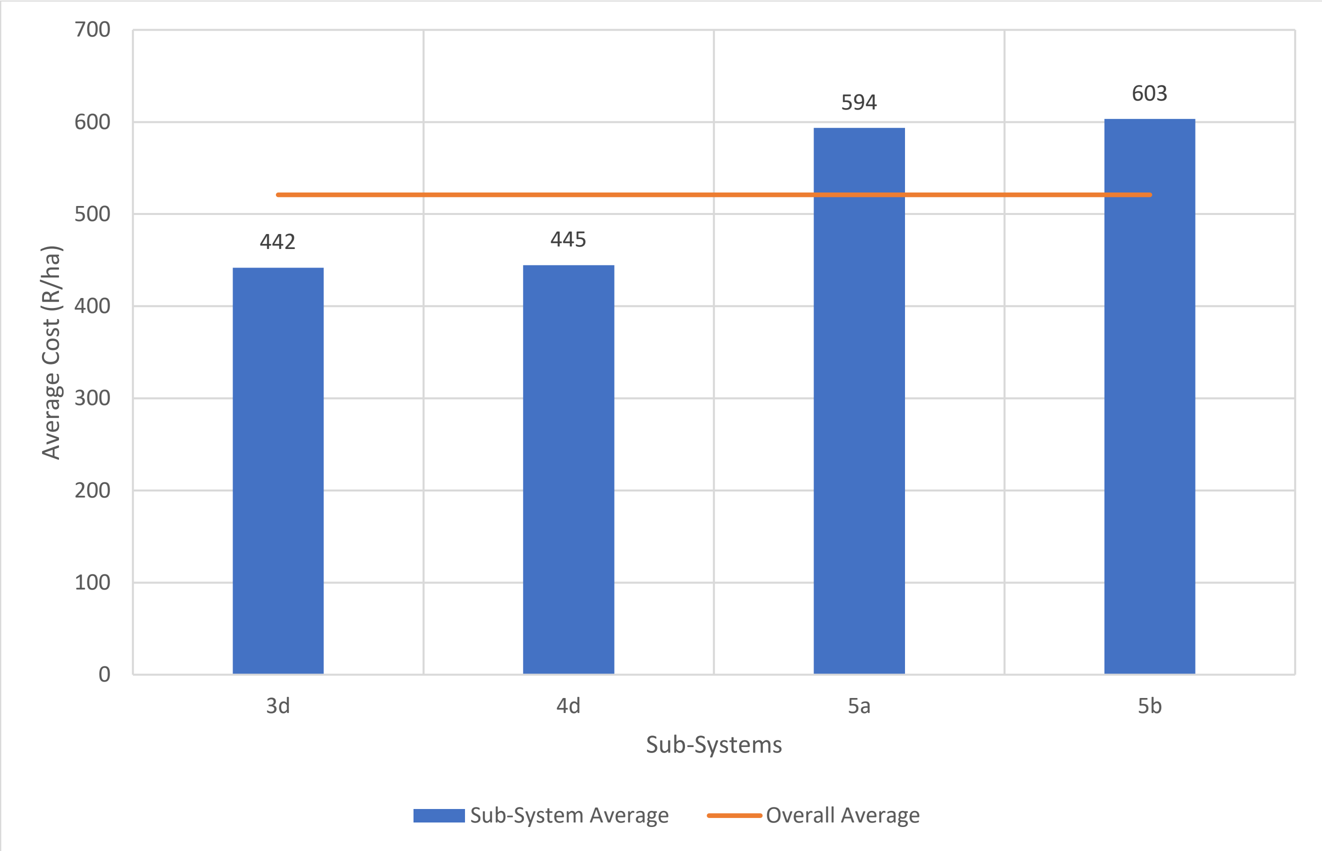


Figure 5.24 - The average cost of weed control for canola from different sub-systems over a 19-year period from 2002 - 2020. The line depicts the overall average cost of all sub-systems tested.

The overall average cost of weed control for all the sub-systems combined was R 521/ha (Figure 5.24). The average cost of weed control for sub-systems 5a (WCWL) and 5b (WBCWBL) was very similar and both were above the overall average. Sub-systems 3d (PWPC) and 4d (PPCW) also had similar average weed control costs, both of which were below the overall average.

The higher average weed control costs for sub-systems 5a (WCWL) and 5b (WBCWBL) could be attributed to the omission of pastures in these systems. They are pure cash-cropping systems and cash crops have higher weed control costs in general when compared to pastures. The poor soil type in one repetition of sub-system 5a (camp 11) also increased the average weed control costs, as mentioned before. Sub-systems 3d (PWPC) and 4d (PPCW) both had two pasture years, one wheat year and one canola year, just in different sequences. This could explain the very similar average weed control costs (Figure 5.24). The two pasture years also decreased the average weed control costs of these two sub-systems in comparison to those for the continuous cash-cropping systems.

5.3.3.3) Seed

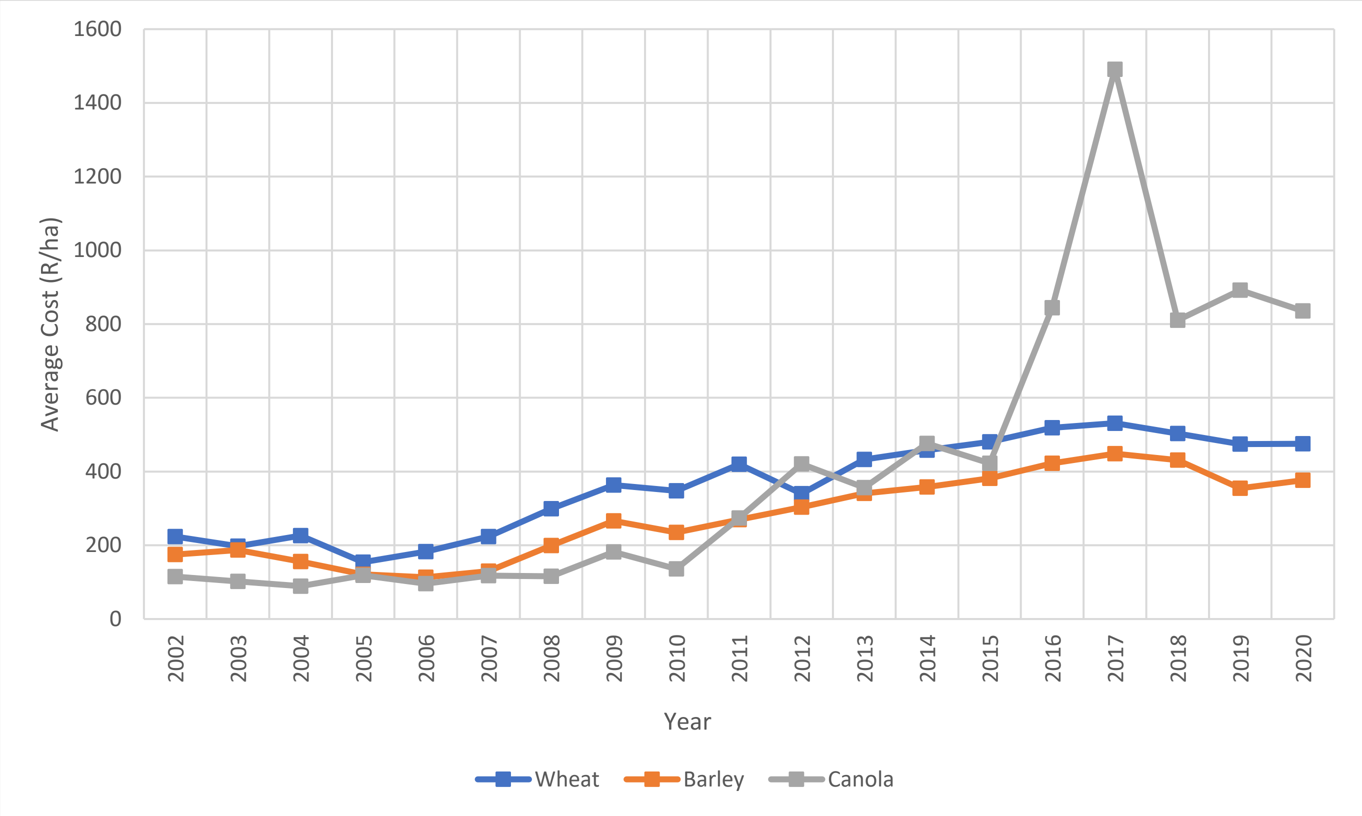


Figure 5.25 - The average annual cost of seed for wheat, barley and canola from 2002-2020.

The average annual seed costs for wheat, barley and canola are depicted in Figure 5.25. Only the annual seed costs per crop are shown as the seed costs between sub-systems were very similar each year and were therefore not included. Seed was the third highest input cost in general for wheat and canola, and was the fourth highest input cost for barley, following fungicide.

The average annual seed costs for wheat, barley and canola followed a similar trend from 2002 until 2010. From 2010 onwards, the average annual seed costs for canola became more varied and then spiked in 2016 and 2017. After 2017, the canola seed price dropped again, but remained far higher than for wheat and barley. The average annual seed prices of wheat and barley increased gradually over time, with the seed price of wheat always being slightly higher than that of barley, but still following the same yearly trends. The varied seed cost for canola was mainly due to cultivar choice. As mentioned previously, the main cultivar of choice for canola was a TT cultivar - known for its resistance to the herbicide triazine which could be used to kill broadleaf weeds. The seed for this cultivar is often more expensive and experienced large price fluctuations which impacted the average annual seed costs for canola.

5.3.3.4) Fungicide

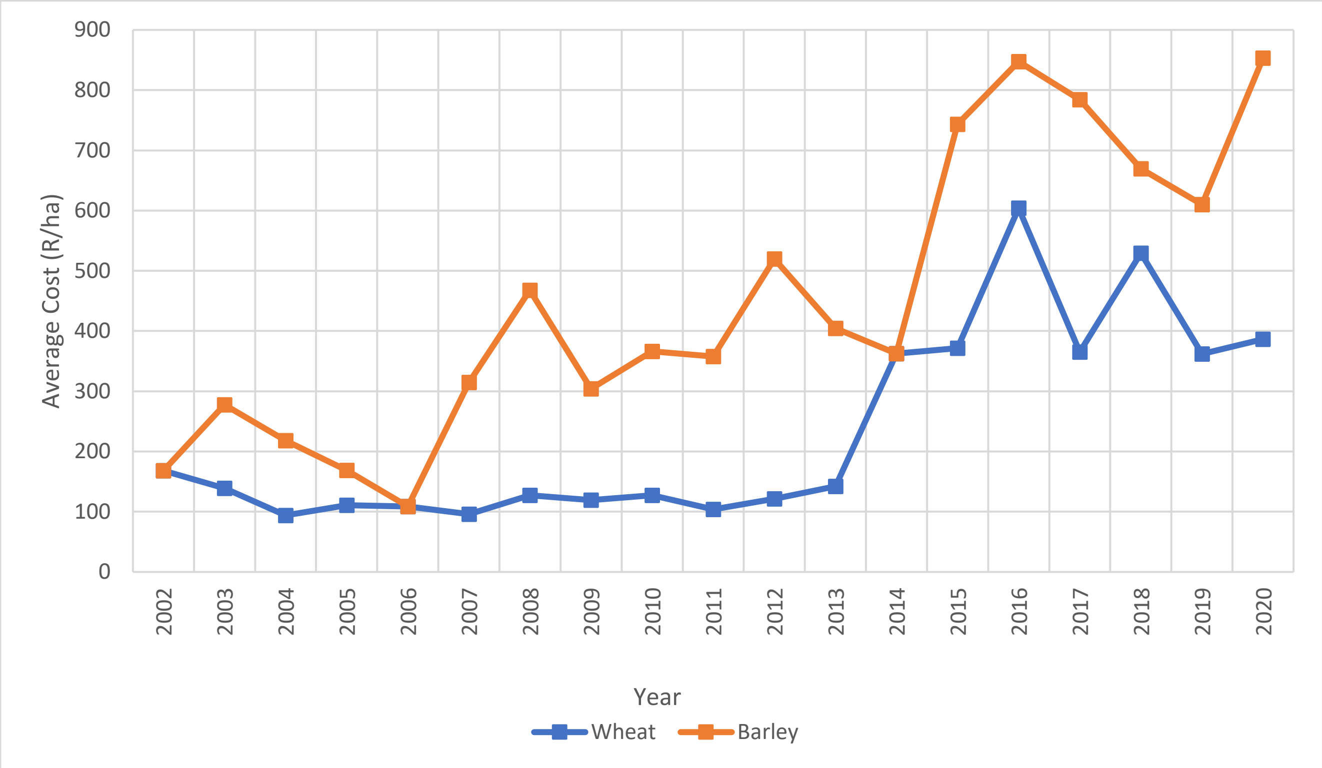


Figure 5.26 - The average annual cost of fungicide for wheat and barley from 2002 - 2020.

The average annual fungicide costs for wheat and barley are shown in Figure 5.26. The fungicide costs for canola were not included as these were minimal. Fungicide was the third highest input cost for barley and fourth highest for wheat.

The average annual cost of fungicide for barley was far more varied than that of wheat and remained higher than that of wheat for the entire trial period (Figure 5.26). Average fungicide costs were highest for wheat in 2016 and highest for barley in 2020. Fungicide costs were lowest for barley in 2006 and lowest for wheat in 2004. The cost of fungicide increased more steeply for barley than it did for wheat over the 19-year trial period. This was due to barley being more susceptible to fungal infection than wheat, increasing the fungicide costs for barley.

5.3.4) Individual input costs over time for all sub-systems

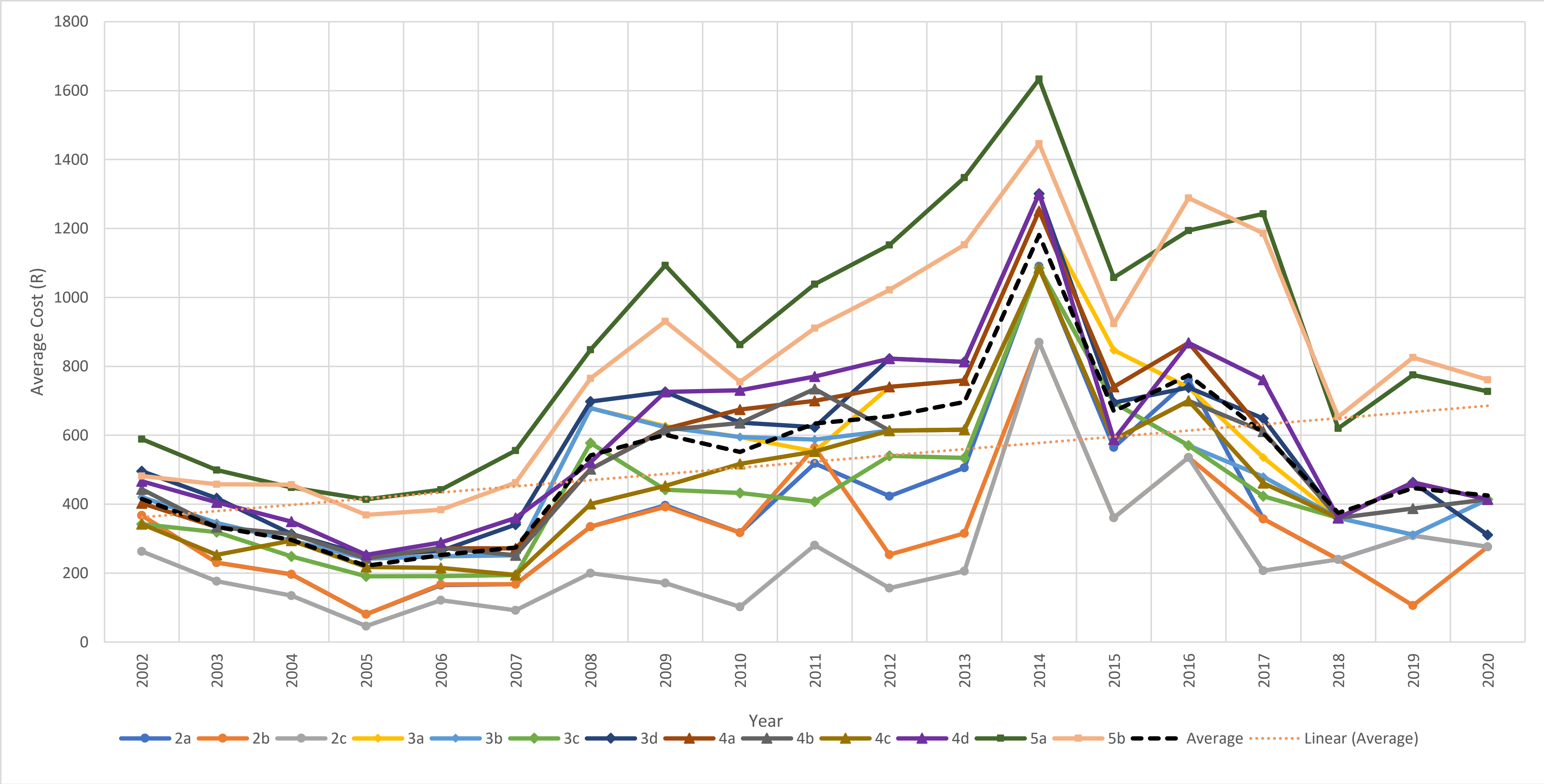


Figure 5.27 - The average annual cost of fertiliser for each sub-system from 2002-2020.

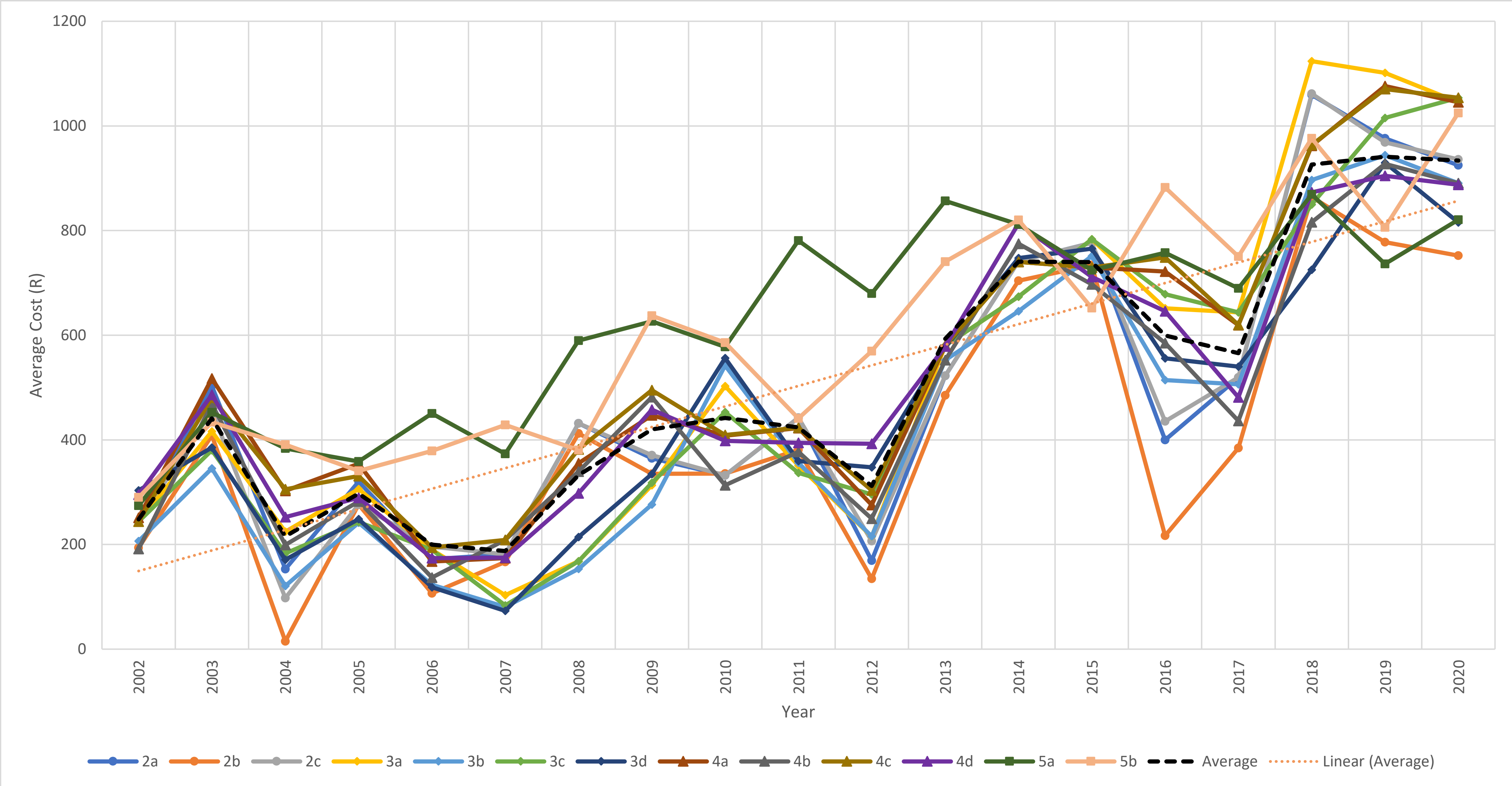


Figure 5.28 - The average annual cost of weed control for each sub-system from 2002-2020.

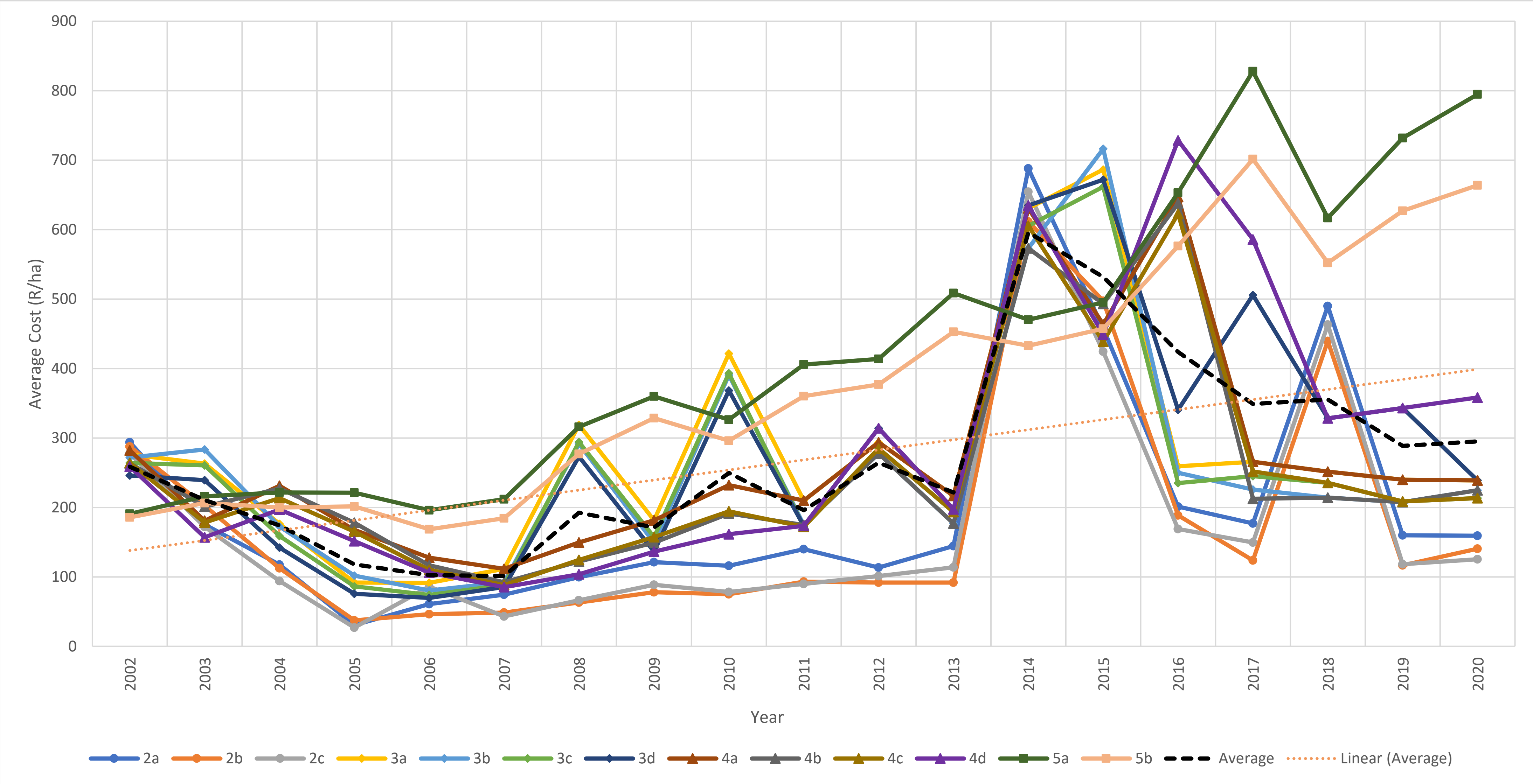


Figure 5.29 - The average annual cost of seed for each sub-system from 2002-2020.

5.3.4.1) Fertiliser over time

All sub-systems followed similar annual trends in fertiliser costs (Figure 5.27). There was a spike in fertiliser costs for all sub-systems in 2014, after which there was a drastic decrease in costs for 2015, increasing again in 2016 and then gradually decreasing towards the end of the trial period. The drop in fertiliser costs might have been due to the switch from more expensive composite fertiliser to mono-ammonium phosphate fertiliser during the later years of the trial. Sub-systems 5a (WCWL) and 5b (WBCWBL) constantly had far higher fertiliser costs than all other sub-systems, with 5a being above 5b until 2015, after which they became very similar. As discussed previously, this could be attributed to the omission of pastures in these systems, which required less fertiliser on average than cash crops. Another reason is the poor soil quality in one repetition of sub-system 5a (WCWL) which needed more fertiliser than other camps.

Sub-systems 2a (PPW), 2b (PPO) and 2c (PPB) had lower average annual fertiliser costs than most other sub-systems over the entire trial period. Sub-system 2c (PPB) routinely had the lowest average fertiliser costs, except for in 2019, when 3b (PPO) had a lower average fertiliser cost. Sub-system 2a (PPW) had nearly identical annual average fertiliser costs to sub-system 2b (PPO) until 2011 after which 2a had higher annual fertiliser costs than 2b, but these costs became similar again from 2017 onwards. The generally lower average annual fertiliser costs seen for sub-systems from system 2 is principally due to pastures making up 67% of the three-year rotations whilst cash crops only accounted for 33% of the rotation. Pastures typically have lower average fertiliser costs than cash crops and the large proportion of pastures in the rotation systems from system 2 reduced the average annual fertiliser costs for these sub-systems accordingly.

Over the 19-year period, the average cost of fertiliser increased from 2009 until 2017, but then decreased and stabilised for all sub-systems towards the end of the trial period. Overall, fertiliser costs did increase over time (from below R 400/ha in 2002 to around R 700/ha in 2020), but only marginally when compared to the steep increases in other input costs such as weed control, which were most likely due to inflation. Up until 2017 a tine planter was being used, from 2017 onwards a disc planter was used which decreased the amount of fertiliser used during planting.

The overall decline in average fertiliser costs for all sub-systems after 2017 (Figure 5.27) indicated an improvement in general soil health and fertility. Therefore, lower levels of external inputs such as fertilisers were needed to maintain good yields. This reduced input costs, allowing for more profitability, making these cropping systems more sustainable over the long term (Strauss, 2021).

5.3.4.2) Weed control over time

The overall average cost of weed control increased steadily over the trial period, from just below R 200/ha in 2002 to more than R 800/ha in 2020 as shown in Figure 5.28. Sub-systems 5a (WCWL) and 5b (WBCWBL) had higher average weed control costs than other sub-systems from 2004 until 2017. Both sub-systems have similar average weed control costs to other sub-systems in 2018 but then dropped below other sub-systems in 2019. Both increased in 2020 with sub-system 5b (WBCWBL) increasing far more steeply than 5a (WCWL) which remained fairly low in comparison to other sub-systems (Figure 5.28). As mentioned previously, both sub-system 5a and 5b were continuous cash-cropping systems, which had higher average weed control costs in general compared to systems including pastures.

The average costs of weed control for sub-systems 2a (PPW), 2b (PPO) and 2c (PPB) were often below those of other sub-systems with 2b (PPO) often being the lowest. This could also be attributed to the higher proportion of pastures making up rotation systems in system 2, with cash crops only accounting for 33% of the rotation systems. The cost of weed control for pastures was generally lower than that of cash crops and two consecutive pasture years (as in system 2) gave more time for weed cycles to be truly broken before the subsequent cash cropping year.

Sub-system 3a (PWPW) had relatively low average weed control costs until around 2015, after which these costs increased drastically with 3a (PWPW) having the highest weed control costs in 2018 and 2019. This could be attributed to poor pasture regeneration in 2018, due to drought, which had a knock-on effect on weed control due to the lack of permanent organic soil cover.

The overall increase in average weed control costs over time was far steeper than that of fertiliser over time (Figure 5.28). Weed problems are common in CA systems but have been seen to decrease over time as the system becomes more established and self-sufficient. The prices of different herbicides have increased steadily over the years, so even if the levels of herbicides used may have declined, the price increases still raised the average cost of weed control.

5.3.4.3) Seed over time

The overall annual average cost of seed increased considerably over the trial period, from about R 150/ha in 2002 to R 400/ha in 2020 (Figure 5.29). The average seed costs for sub-systems 5a (WCWL) and 5b (WBCWBL) increased steadily over time, being well above the overall average most of the time. This consistent rise in costs might be because there were only cash crops in these sub-systems which had more predictable, steady seed costs than those for pastures which can vary greatly between years, depending on whether they re-established naturally or not. The seed costs for sub-system 5a (WCWL) were always slightly higher than those for 5b (WBCWBL).

The average seed costs of sub-systems 2a (PPW), 2b (PPO) and 2c (PPB) were consistently lower than those of other sub-systems throughout the trial period. The average seed costs for those sub-systems in system 3 followed similar trends and spiked above the costs of other sub-systems in 2008 and 2010. This was due to the pasture camps in system 3 that had to be re-established in 2008 and 2010, which drastically increased the average annual seed cost. There was an immense spike in seed costs for all sub-systems, except those in system 5, in 2014. Seed costs stayed high for system 3 in 2015 and decreased for most sub-systems from 2016 onwards.

5.4) Conclusion

Chapter 5 analysed the economic data from the trials run at Tygerhoek from 2002 until 2020. This included the gross margin analyses data as well as the input cost data. This was done to compare profitability between systems. The gross margin analyses took into account the gross income (GI), allocatable variable costs (AVC) and gross margins (GM) between systems and sub-systems, as well as for different crops over time. The overall average GMs of systems 2, 3 and 4 followed similar trends over the duration of the trial whilst those for system 5 were more varied and dropped far below the other three systems after 2017. Systems 3 and 4 both contained four-year rotation systems that were made up of two pasture years and two cropping years. System 2 only had three-year rotation systems, two of which were pasture years and one of which was a cropping year. Cropping years usually brought in higher GIs than pasture years and the two cropping years in systems 3 and 4 will increase the overall average GM of these systems when compared to system 2 which only had one cropping year. System 5 was made up of only continuous cash crops and achieved high GIs, but also had higher AVCs than other systems, due to the increased need for fertiliser and weed control amongst other things. This decreases the overall GM for system 5. One replicate of sub-system 5a (WCWL) was planted in camp 11 which was known to produce lower yields, and this decreased the GI of sub-system 5a (WCWL) as a whole and also increased AVC's, lowering the overall GMs for the sub-system. Sub-systems 4c (PPWB), 3c (PWPB) and 3a (PWPW) showed the highest overall average GM's. All three of these sub-systems were comprised of four-year sequences, made up of two pasture years and two cropping years (with the crops being either wheat or barley). This might be attributed to the higher average yields seen for these sub-systems as well as the lower fertiliser and weed control costs after the pasture years.

Annual rainfall was also seen to impact the GMs of the four main systems as the GMs of all systems declined in drier years due to lower yields and increased input costs. However, as seen in the yield results, the systems showed increased resiliency to drought conditions as was illustrated by the quick bounce-back of GMs after the three drought years, during which GMs had dropped considerably.

Gross margin analyses were done for wheat, barley and canola. The average GI for wheat was seen to steadily increase over the trial period although drier years did show a decline in overall average GI. The overall average AVCs for wheat also increased over time but remained fairly constant from 2013 onwards and did not rise as steeply as the average GI over time. Wheat GMs also steadily increased over the trial period. The wheat sub-systems with the highest average GMs over the 19-year trial period were 3d (PWPC), 4d (PPCW) and 4c (PPWB). All three of these sub-systems had two pasture years and two cropping years. The two sub-systems with the highest GM's, 3d (PWPC) and 4d (PPCW), both had two pasture years, a wheat year and a canola year which was seen to be a profitable grouping of crops in the long-term. Wheat from system 5 was seen to have markedly lower GMs than wheat from other systems which is mainly due to the higher AVCs seen for that system as the continuous cash cropping sub-systems often required higher input levels, increasing input costs. Sub-system 4a (PPWW) had a lower average GM than other sub-systems which might have been caused by the two years of wheat monoculture which was shown to have lower wheat yields on average.

The average annual GI for barley was also seen to steadily increase over the years, with some drier years showing a lower GI due to lower yields. The average annual AVCs for barley also increased over the trial period but remained fairly constant from around 2010 onwards. The average annual GMs also increased over time with only two years showing a negative GM, 2004 and 2019, both of which were severe drought years with low yields. The GMs showed a steep increase after 2011 which could be attributed to better cultivar selection which resulted in higher yields as well as lower general AVCs as the systems became more established and self-sufficient.

There were only four sub-systems that included barley, namely 2c (PPB), 3c (PWPB), 4c (PPWB) and 5b (WBCWBL). The sub-systems including pastures (2c, 3c and 4c) had similar GMs over the 19-year trial period, all of which were higher than the overall average GM for sub-system 5b (WBCWBL) which did not have a pasture element. This might have been due to 5b having a lower overall average GI and higher average AVCs than the other three sub-systems. The added nitrogen and improved weed control, associated with the inclusion of legume pastures, increased yields and reduced input costs for sub-systems 2c (PPB), 3c (PWPB) and 4c (PPWB). Sub-system 5b (WBCWBL) did not have these added benefits which contributed to the lower overall average GM of the sub-system.

The average annual GI for canola showed a steady increase over the trial period, with the average GI becoming markedly higher from 2011 onwards. This might be due to better cultivar selection which increased yields. As mentioned before, mainly TT canola cultivars were used which are associated with slightly lower yields, but also had lower weed control costs. Over time, there were improvements in cultivar selection which reduced the limiting effect of the TT cultivars on yield. The average annual AVCs for canola also increased over time but not as steeply as the average annual GIs. The average annual GMs for canola also increased over the trial period but a negative average GM was seen in 2004 and 2015, as well as an unusually low GM in 2017. The low average GM seen in 2004 and 2017 might have been due to lower growing season rainfall which resulted in lower yields and increased AVCs. In 2015, strong winds destroyed canola in two of the four canola sub-systems which drastically reduced yields.

There were only four sub-systems that included canola, namely 3d (PWPC), 4d (PPCW), 5a (WCWL) and 5b (WBCWBL). Sub-systems 3d and 4d both contained a 50:50 pasture crop ratio whilst sub-systems 5a and 5b were continuous cash cropping systems. Sub-systems 3d (PWPC) and 4d (PPCW) had higher overall average GIs and GMs, and lower average AVCs, than sub-systems 5a (WCWL) and 5b (WBCWBL). This might have been due to the higher yields and reduced inputs for sub-systems 3d and 4d due to the benefits provided by the two pasture years. Sub-systems 5a and 5b did not have these benefits. Sub-system 5a (WCWL) had one repetition planted in camp 11 which had lower yields and high weed pressure. Sub-system 5b (WBCWBL) had more comparable margins to the sub-systems that included pastures (3d and 4d), but still performed poorly.

There were nine main input costs recorded for each camp each year. These were: fertiliser, weed control, pest control, fungicide, lime, fuel, seed, contractors and repairs and maintenance. The three most prominent input costs were found to be fertiliser, weed control and seed for all sub-systems overall. For system 2, weed control made up a larger proportion of the average total input cost than fertiliser, whilst for system 5 fertiliser made up a larger proportion than weed control. The proportions between fertiliser and weed control costs were split more evenly for systems 3 and 4. The lower proportion of fertiliser costs seen for system 2 could be explained by the higher soil nitrogen levels following the two pasture years and the low to no fertiliser required during pasture years. The higher proportion of fertiliser costs for system 5 might have been linked to the lack of pastures in this system which resulted in lower soil nitrogen levels and higher fertiliser needs.

System 5 had a higher average total input cost than other systems, whilst system 2 had the lowest average total input cost over the 19-year trial period. Systems 3 and 4 had similar average total input costs. Pasture years were seen to have lower average total input costs in general than cropping years. This might have been the reason for system 2 having a lower average total input cost, as this system was only made up of three-year rotations, with two pasture years and one cropping year.

System 5 on the other hand was made up of only cropping years, increasing the overall average total input cost. When considering the average total input cost over time for all the sub-systems, sub-system 2b (PPO) was consistently the lowest, whilst sub-system 5a (WCWL) was consistently the highest. Sub-system 2b (PPO) had two pasture years, which had lower input costs than cropping years, and one year of oats which are also known to have lower input costs than other cash crops. Sub-system 5a (WCWL), as mentioned before, had one repetition planted in camp 11 which had higher average input costs than other camps due to the poor soil health and weed problems. Input costs for all sub-systems rose steadily over the trial period as product prices increased in general. Sub-systems from systems 2, 3 and 4 rose steadily until 2015 after which they declined. This might have been due to the systems stabilising and becoming more self-sufficient, lowering the need for external inputs. System 5, however, still showed a steady increase in total input costs.

When comparing input costs between different crops, canola had the highest overall average total input cost over the 19-year period, followed by wheat and then barley. For wheat and canola, the three main input costs were fertiliser, weed control and seed. However, the three main input costs for barley were fertiliser, weed control and fungicide. This could have been because the barley cultivars available in the earlier years of the trial were more susceptible to disease but this improved over time as more resistant cultivars became available. The seed costs for barley were the fourth highest input cost but were still lower than those for wheat and canola as barley had a lower seeding rate.

The wheat sub-systems with the lowest overall average total input cost were 2a (PPW), 3c (PWPB) and 3a (PWPW). All three of these sub-systems included two pasture years, which assisted in decreasing weed control and fertiliser costs. The wheat sub-systems with the highest overall average total input cost were 5a (WCWL), 5b (WBCWBL) and 4c (PPWB). The two sub-systems from system 5, the continuous cash cropping system, were known to have higher input costs in general since these systems were only made up of cropping years. Sub-system 5a (WCWL) had one repetition planted in camp 11 which also increased costs. For the barley sub-systems, sub-systems 2c (PPB), 3c (PWPB) and 4c (PPCW) had similar overall average total input costs, but sub-system 5b (WBCWBL) had a higher overall average total input costs. This can once again be attributed to 5b (WBCWBL) being a continuous cash cropping system. The same trend was seen for the canola sub-systems, where sub-systems 3d (PWPC) and 4d (PPCW) had lower overall average total input costs than sub-systems 5a (WCWL) and 5b (WBCWBL) – the two continuous cash cropping sub-systems..

Fertiliser and weed control costs for wheat, barley and canola were examined in more detail individually over the trial period. Average annual fertiliser costs were the highest for canola, followed by wheat and then barley. The annual fertiliser costs for all three crops increased steadily until 2017, after which they dropped and became very similar for all three crops. This was due to a disc seeder being used instead of the original tine seeder, which used far less fertiliser during planting. Sub-systems from system 5 had consistently higher overall average fertiliser costs for all three crops. Sub-systems from system 3 generally had the lowest overall average fertiliser costs for all three crops and sub-systems from system 4 generally had higher fertiliser costs than those from system 3.

Average annual weed control costs rose steadily for both wheat and barley but decreased for canola from 2014 onwards. The increase for wheat and barley could be attributed to the rising prices of herbicides, so although the level of inputs may have decreased, the overall cost increased due to inflation. Canola had very high average annual weed control costs between 2008 and 2014, which was caused by the limited number of suitable herbicides available, all of which were expensive. As more cultivars improved and more herbicides became available the average weed control costs for canola declined. For wheat sub-systems, the highest overall average weed control costs were for sub-systems in system 5 whilst the lowest were from sub-systems in system 2. Wheat sub-systems from systems 3 and 4 had similar overall average weed control costs. For barley, the overall average cost of weed control for sub-system 5b (WBCWBL) was higher than those of the other three sub-systems. Barley from sub-system 4c (PPWB) had the second highest overall average weed control cost, followed by 3c (PWPB) and 2c (PPB). Once again showing lower average weed control cost for sub-systems that contained pastures. The overall average weed control costs for canola from sub-systems 5a (WCWL) and 5b (WBCWBL) were higher than from sub-systems 3d (PWPC) and 4d (PPCW), which were very similar.

The average annual seed costs for wheat and barley slightly increased over the trial period, with the seed costs for wheat always being slightly higher than for barley. Average annual canola seed prices spiked in 2016 and 2017, after which they dropped again but remained higher than those for wheat and barley. The use of TT cultivar canola may have caused the spike in prices, as this cultivar is often more expensive and has more drastic price fluctuations than the seed for wheat and barley. The average annual fungicide costs for wheat and barley were considered over time, but not for canola as canola had minimal fungicide costs. Average annual fungicide costs were consistently higher for barley than for wheat. There was also a steeper increase in fungicide costs for barley than for wheat which was due to barley being more susceptible to fungal disease than wheat.

The overall average annual costs of fertiliser, weed control and seed for all sub-systems, over the entire trial period, were also considered. Sub-systems from system 2 had consistently lower average annual fertiliser costs than other sub-systems whilst sub-systems from system 5 had consistently higher annual fertiliser costs. For sub-systems from systems 2, 3 and 4, fertiliser costs climbed steadily until 2017 after which they declined. The fertiliser costs for system 5 however, continued to increase. The same trends occurred for the average annual weed control costs for all sub-systems over time. Sub-systems from system 5 consistently had the highest annual weed control costs whilst sub-systems from system 2 had the lowest. Overall, the average costs of weed control increased more steeply than those for fertiliser, as herbicide prices rose more drastically, and fertiliser usage decreased over time. The average annual cost of seed followed the same trend as for both fertiliser and weed control costs with system 5 having had the highest costs whilst system 2 had the lowest. System 2 was predominantly pastures which had very low seed costs as they usually re-established by themselves, whilst system 5 consisted of only cash crops, all of which required seed to be bought each year. System 5 also included lupines, the seed for which is very expensive.

Chapter 6 – Conclusion, Summary & Recommendations

6.1) Conclusion

The growing world population and increased demand for food, that needs to be produced with increasingly limited natural resources, is highlighting the necessity for more efficient and sustainable methods of food production. Conservation agriculture (CA) is recognised as a more holistic approach to sustainable agriculture and is increasing in popularity worldwide. CA comprises of three main principles:

- **Minimal- or no-tillage**
- **Permanent organic soil cover; and**
- **Increased diversity through crop rotations.**

Simultaneous adoption of all three principles aims to make more efficient use of natural resources to increase the long-term sustainability of farming systems. A host of benefits are associated with the adoption of CA. These include improved overall soil health, decreased soil degradation and erosion and improved water infiltration and retention. All of which act to increase crop yields and reduce input costs. However, there are also challenges associated with CA adoption. It may take some time for a CA system to fully establish and start showing benefits. During this time there may be periods with little to no profits, which can be financially tough on producers. CA is also a knowledge-intensive process during which producers require guidance and support from the relevant authorities.

CA started gaining popularity in the USA in the 1930's as the destructive effects of conventional tillage became more apparent. CA practices then spread to Australia, South America and Asia. Africa has only recently started to show increased rates of CA adoption. In a water-scarce country such as South Africa, the improved drought resiliency associated with CA systems is a major advantage to dryland (rain-fed) cereal producers. CA is a concept that encompasses all aspects of the individual farm and can be adapted to fit specific social and ecological conditions. The Western Cape Province has been the forerunner in the adoption of CA in SA, especially in winter cereal producing areas such as the Swartland and Overberg.

The focus of this thesis is on short-cycle crop rotation systems in the Overberg region. The Overberg has a Mediterranean climate with hot, dry summers and cool, wet winters. The most common cash crops cultivated in the area are wheat, barley, canola, oats, and lupines. There is a high rate of CA adoption in this area and the experimental trials run at Tygerhoek Experimental Farm (which serves as the information basis for this research project) are managed according to CA principles. A particularly common practice in the Overberg is the use of crop rotation systems, usually including a pasture aspect and livestock (sheep). The Tygerhoek trials focus on short rotation systems, applying different sequences of cash crops and pastures.

Previous studies on the trials at Tygerhoek included a financial analysis, soil profiling and an analysis of the livestock aspect of the farm. Although a financial analysis of the crop rotation trials had been done, there is still a need for the evaluation of identified critical physical/biological and ecological drivers of profitability underlying long-term sustainability within selected crop rotation systems at Tygerhoek.

There were five main short rotation systems at Tygerhoek, one of which is not relevant to this study (system 1 which was only lucerne pastures). Each main system had smaller sub-systems with different crop sequences, a more detailed description of these systems was given in Chapter 3. Each year, detailed yield, quality, gross margin, and input cost data were recorded for each camp. The methods of analysis for this data were broken up into two main sections, namely the ecological data (yields and quality) and the economic data (gross margins and input costs). This allowed for a profitability comparison between systems and sub-systems, as well as an analysis of the physical/biological and ecological factors driving the profitability. This helped to assess the long-term sustainability of the different systems.

The yield and quality data were compared between systems, sub-systems and crops. The crops under focus were wheat, barley and canola which are the main cash crops grown in the Overberg region. Climatic conditions, cultivar choice and the position of different camps within the crop rotation sequence had an impact on crop yields and quality. The one repetition of sub-system 5a (WCWL) that fell on a specific camp, camp 11, characterised by self-compacting soil, was consistently the worst performing sub-system in terms of both crop yield and quality. There were signs of increased drought tolerance over time which could be attributed to the improvements in soil structure under CA management, amongst other benefits. With regards to crop yields, sub-systems that included leguminous pastures consistently outperformed sub-systems without a pasture component. This was mainly due to the increased soil nitrogen available to crops following pasture years which can be attributed to the nitrogen fixation of the leguminous pastures. There was less weed pressure in crops following pastures as these pasture years acted as a “break” in pest, disease and weed cycles and had a mitigating effect on these issues in subsequent crop years. Both these factors increased yields for sub-systems including a pasture component. The combination of two pasture years, a canola year and a wheat year was shown to maximise both wheat and canola yields, and this combination frequently showed the highest yields. The lowest yielding sub-systems were usually from system 5, the continuous cash cropping system, as was true for wheat, canola and barley yields.

The quality indicators used for wheat were hectolitre mass (HLM) and protein content. The average HLM of wheat increased over the trial period whilst the average protein content decreased slightly. Wheat from sub-systems containing pastures was most often classified as super-grade whilst wheat from system 5 (the continuous cash cropping system) generally met the HLM requirements but not the protein requirements for BS and was usually classified as B1. The quality indicators used for barley were kernel plumpness and nitrogen content. Barley from all sub-systems, except for sub-system 2c (PPB) met both the plumpness and nitrogen content requirements to be classed as malt grade. Barley from sub-system 2c (PPB) met the plumpness requirements but not the nitrogen content requirements. This may have been caused by the high levels of soil nitrogen available to barley following the two legume pasture years which might have pushed the nitrogen content of the kernels above that required to be classified as malt grade.

The economic data analysed included the gross income, allocatable variable costs, gross margin and input costs for each individual camp each year from 2002 until 2020. As seen with the yield and quality data, climatic conditions, cultivar choice and the camp layout within the trial also impacted on gross margins. Crops grown during drier years usually had lower yields resulting in lower gross margins. The repetition of sub-system 5a (WCWL) planted in camp 11 had markedly lower gross margins and higher input costs compared to the second repetition planted in camp 18. This lowered the overall economic performance of sub-system 5a.

When looking at the profitability of different sub-systems in general, those consisting of a combination of two pasture years, one barley year and one wheat year obtained the highest gross margins. This might have been due to the higher soil nitrogen levels and lower weed pressure in crop years following pasture years, which increased yields and reduced input costs. Wheat from sub-systems with two pasture years and two cropping years (wheat and either barley or canola) had the highest gross margins. The three wheat sub-systems with the highest gross margins over the entire trial period, all had wheat which followed on from pastures or canola. The canola years, like the pasture years, also reduced weed pressure in the successive wheat year – increasing yield and decreasing input costs which raised the gross margins. The same trends were seen for barley. Barley from sub-systems containing pastures continually showed higher gross margins than barley from the continuous cash cropping sub-system. This was seen again for canola from sub-systems with pastures compared to from sub-systems without pastures. The continuous cash cropping sub-systems returned the lowest gross margins for all three crops. Although sub-systems 5a (WCWL) and 5b (WBCWBL) mostly brought in high gross incomes, the allocatable variable costs for these sub-systems were also higher than those for other sub-systems. The higher allocatable variable costs decreased the gross margins for these sub-systems considerably. This might have been due to the lower soil nitrogen levels in sub-systems from system 5 compared sub-systems that included a pasture component, as well as the higher weed prevalence seen in system 5. Both of these factors reduced yields and increased input costs.

An input cost analysis was done to assess input costs between crops, systems and sub-systems. The changes in individual input cost items over time were included. The input costs discussed in this thesis were: fertiliser, weed control, pest control, fungicide, lime, fuel, seed, contractors and repairs and maintenance. The three input cost items that most directly contributed to the total cost were fertiliser, weed control and seed cost. Weed control was the most prominent input cost for system 2 and fertiliser was the most prominent for system 5. The fertiliser and weed control costs were similar for systems 3 and 4. System 5 had the highest average total input cost over the trial period whilst system 2 had the lowest. This might have been due to system 2 only having three-year crop sequences – two of which are pasture years with only one cash cropping year. Input costs for pasture years were lower than for cropping years. Therefore, systems made up of predominantly pasture years showed lower total input cost than those with an equal ratio between cash crops and pastures or with only cash crops. Sub-system 5a (WCWL) had particularly high input costs. This could have been due to the one repetition planted in camp 11. The average annual total input cost rose steadily for systems 2, 3 and 4 until 2015. After which the average total input costs for these systems decreased and stabilised at a lower level. This might have been due to the systems becoming more established and self-sustaining, thus requiring fewer external inputs as the benefits of CA took effect. The annual total input cost for system 5 continued to rise steadily over the trial period and did not experience the same decrease as for the other systems. The average rise in costs for all inputs could be attributed to general price increases over time. The only way of lowering input costs was to lower input levels.

When comparing input costs between crops, canola had a higher average total input cost than wheat and barley. The three main contributors to the average total input cost for wheat and canola were fertiliser, weed control and seed. The three main contributors to the average total input cost for barley were fertiliser, weed control and fungicide. The barley cultivars used in the earlier years of the trial were more susceptible to fungal diseases and required high levels of fungicide but this improved over time as more disease resistant cultivars became available. Barley also had a lower seeding rate than wheat and canola which lowered seed costs. For all three crops, sub-systems from system 5 showed the highest average total input costs. Wheat from sub-systems where wheat followed a pasture year consistently showed lower average total input costs overall. As previously mentioned, this might have been due to the increased soil nitrogen and lowered weed pressure in crops following leguminous pastures. Similar trends were seen for barley and canola, where the average total input cost for sub-systems containing pastures were lower than for the continuous cash cropping sub-systems.

Fertiliser, weed control and seed costs for each individual crop were examined in more detail over time. Up until 2018 a tine planter was used to plant all three crops. From 2018 onwards, a switch was made to a disc planter. The disc planter used lower amounts of fertiliser during planting. This was reflected in the average annual fertiliser costs for all three crops, which dropped off from 2018 onwards. Wheat, barley and canola from systems 2 and 3 generally had lower average annual fertiliser costs than from system 4. Cash crops from system 5 consistently had the highest average annual fertiliser costs.

The average annual weed control cost for both wheat and barley was seen to rise steadily over the trial period. This was mainly due to the increasing costs of herbicide each year. The average annual weed control cost for canola, however, was high between 2007 and 2015, but then decreased to below the average weed control costs for wheat and barley. This might have been caused by the limited number of canola herbicides available during the initial years of the trial, most of which were more expensive than those for wheat and barley. As improved canola cultivars and more herbicides became available, the average annual weed control cost for canola declined. As seen with other input costs, system 5 incurred higher average weed control costs for all three crops than those of other systems. This could be attributed to the lack of "break" years in the continuous cash cropping system. Cultivar selection had a big effect on weed control costs as some cultivars required less herbicide than others, reducing costs.

The average annual seed cost for wheat and barley increased slowly over the trial period, with the average seed cost for wheat always being slightly higher than for barley. The average annual canola seed cost showed more fluctuation and spiked in 2016 and 2017, after which the cost dropped off again but remained higher than the average seed costs for wheat and barley. This might have been due to the use of TT (Triazine Tolerant) canola which was tolerant to herbicides containing triazine, which allowed for improved weed control. TT cultivar seed was subject to more frequent price fluctuations and was usually more expensive than seed for wheat and barley.

When comparing average fertiliser, weed control and seed costs for each sub-system, a noticeable trend emerged. The sub-systems from system 5 had the highest fertiliser, weed control and seed costs. This can be attributed to the omission of pasture years which required less fertiliser and weed control and had very low seed costs, since the pastures mostly re-established naturally. The cash crops following pasture years also had lower fertiliser and weed control costs. System 5, being made up of only cash crops, had higher fertiliser and weed control costs as well as seed costs. This was because each crop needed to be planted each year, unlike the pastures which usually re-established by themselves.

The main objective of this study was to determine the extent to which identified critical drivers promoted the long-term sustainability of different short-term crop rotation systems in the Middle Rûens area of the Overberg. This was broken down into specific research goals. The first of which was to identify and describe the most profitable short rotation systems for the Middle Rûens area. The method used for this was an analysis of the economic data from the experimental trials at Tygerhoek, which included the gross margins, allocatable variable costs, gross incomes and input costs for the different rotation systems. Comparisons of these economic measures were done between systems, sub-systems and crops. This resulted in specific rotation systems being identified which were more profitable over the long-term with regards to gross margins and input costs. The positive impact of higher yields, in combination with reduced input costs, on the overall profitability of the systems was also emphasised. This also highlighted the increased farm resiliency and sustainability seen over time under a CA management approach.

The second research goal was aimed at determining which physical/biological factors underpinned the profitability of each system and to evaluate the factors that drove the profitability of the crop rotation systems. To achieve this, the yield and quality data from the different rotation systems were analysed. This resulted in the identification of certain factors, such as climate and cultivar choice, that strongly impacted both crop yields and quality. The combination of crops and crop sequence in the different rotation systems also played a role in the yields and quality of the crops. The yields and quality of the crops produced had a determining role in the overall profitability of the rotation systems as higher yields produced higher gross margins for the systems.

The following important conclusions were reached:

- The climatic conditions, cultivar choice and location of the crop within the trial layout were important determining factors influencing both crop yield and quality. Drier years showed lower yields and lower quality crops.
- Crops following pasture years had generally higher yields. This can be mainly attributed to the increased levels of soil nitrogen available to the crops as well as the reduced weed pressure after pasture years.
- Wheat from all the systems, except from system 5, usually qualified as super grade. The wheat from system 5 usually fell short of the nitrogen requirements, resulting in it being classified as B1. The barley from all sub-systems, except 2c (PPB), qualified as malt grade. The barley from sub-system 2c often exceeded the nitrogen requirements for malt grade, resulting in it being classed as feed grade.

- Sub-systems from system 5 consistently had the lowest gross margins and highest average total input cost when compared to those from other systems. Although system 5 showed high gross incomes, the high allocatable variable costs brought down the gross margins considerably.
- Rotation systems with the combination of two pasture years, one wheat year and one canola year were the most profitable sub-systems for both wheat and canola.
- Fertiliser costs declined for systems 2, 3 and 4 after 2017, showing a reduced need for high levels of fertiliser in these systems. The fertiliser costs for system 5, however, continued to rise steadily over the entire trial period which showed the CA benefits being realised by the other three systems were not coming into effect in system 5.

6.2) Summary

Chapter 1 started with a brief background and introduction, highlighting the need for more sustainable methods of food production in the face of a growing population and a changing climate. Conservation agriculture has been put forward as a more holistic approach to sustainable agricultural intensification. In South Africa, the Western Cape has the highest CA adoption rates, especially in the winter cereal production regions such as the Swartland and the Overberg. The use of crop rotations is common in these areas and usually consist of cash crops such as wheat, barley, canola, oats and lupines in combination with pastures which often include a livestock aspect. There have been ongoing short crop rotation trials being conducted at Tygerhoek Experimental Farm in the Middle Rûens area of the Overberg. A financial analysis has already been done for these trials but there is still a need for the evaluation of identified critical physical/biological and ecological drivers of profitability for long-term sustainability within selected crop rotation systems at Tygerhoek. This was the main objective for this thesis, and this was accompanied by more specific research goals. These goals included the identification of the most profitable short rotation systems as well as the physical/biological and ecological factors that underpin this profitability.

An overview of relevant literature was presented in Chapter 2. The need for more sustainable agricultural practices was outlined further and the concept of conservation agriculture was introduced. The origins and three main principles of CA were explained in more detail as well as the holistic nature of the concept. The benefits of CA adoption were discussed, highlighting the ways in which CA can assist in enhancing the long-term sustainability of farming systems. There are, however, drawbacks associated with CA and these challenges to CA adoption were also investigated. CA has been adopted to varying degrees around the world and has recently started growing in popularity in Sub-Saharan Africa. In South Africa, the Western Cape Province has the highest rates of CA adoption – particularly in winter cereal areas such as the Overberg. Many farmers have adopted one or two CA principles but fewer have adopted all three simultaneously, which is recommended to achieve the full potential of a CA system. The use of crop rotations in the Overberg is common and the crops usually grown in these rotation systems include wheat, barley, canola, oats, lupines, triticale and pastures. Many farmers also incorporate a livestock aspect such as sheep.

Chapter 3 describes Tygerhoek Experimental Farm as a whole, such as why the trials were started, the geographical location of the farm as well as an outline of the rotation systems being investigated. All the trials on Tygerhoek have been managed according to CA principles and consist of the following crops: wheat, barley, canola, oats, lupines and pastures. There are five main rotation systems, the first of which is not used for this study as it is 100% lucerne system. Systems 2, 3 and 4 are made up of different combinations of pastures and crops whilst system 5 is made up of only continuous cash crops. There are multiple sub-systems under each main rotation system. Detailed recordings of yield, quality, gross income, allocatable variable costs, gross margins, input costs and livestock data were taken each year for each camp. Chapter 3 also includes an explanation of how the financial data were calculated. The specific requirements for the wheat and barley quality indicators were also shown, as well as an explanation of the rating system used to compare quality between sub-systems.

The results and discussion for this thesis consisted of two main chapters. Chapter 4 discussed the yield and quality data from the trial and Chapter 5 discussed the economic data and input costs. Chapter 4 analysed the yield and quality data for wheat, barley and canola between systems, sub-systems and over time. It was seen that crop yields for crops following pastures were often higher than for those sub-systems without a pasture aspect. This was attributed to the nitrogen-fixing abilities of the pastures as well as the reduced weed infestation levels in crops following pastures. The crop yields for sub-systems 5a (WCWL) and 5b (WBCWBL) were consistently lower than those of other sub-systems. This was mainly attributed to the omission of a pasture component in these sub-systems, which resulted in higher weed pressure and less soil nitrogen available to these crops when compared to crops in other sub-systems, all of which contained a pasture component. Sub-system 5a also had one repetition planted in camp 11, which had self-compacting soil, and this had a detrimental effect on the yields, quality, gross margins and input costs for the sub-system. Rainfall was another factor which had a big impact on yields as years with lower growing-season rainfall showed lower yields for all crops. It was shown, however, that over time, the systems became more resilient and better able to tolerate drought conditions.

The quality indicators used for wheat were hectolitre mass (HLM) and protein content. These two measures were compared for wheat from different sub-systems and over time. Wheat from all sub-system, with the exception of wheat from sub-systems 5a (WCWL) and 5b (WBCWBL), consistently met the HLM and protein content requirements for super grade. Wheat from sub-systems 5a and 5b did not meet the protein requirements for super grade and were thus usually classed as B1. The quality indicators used for barley were kernel plumpness and nitrogen content. Barley from all sub-systems met the plumpness requirement for malt grade. Barley from all sub-systems except 2c (PPB) met the nitrogen content requirements for malt grade. This resulted in barley from sub-system 2b usually being classed as feed grade. This was attributed to the higher proportion of pastures to crops (67:33) in this sub-system, increasing the kernel nitrogen content levels above the allowed limit for malt grade barley.

Chapter 5 analysed the economic and input cost data from the trials at Tygerhoek. The gross income (GI), allocatable variable costs (AVC), gross margins (GM) and input costs were compared between sub-systems and crops over the 19-year trial period and annually. Sub-systems from systems 3 and 4 were seen to generally have higher GMs than those from systems 2 and 5. Cropping years are known to bring in more income than pasture years and systems 3 and 4 both had two pasture years and two cropping years, whilst system 2 had two pasture and only one cropping year. This decreased the overall GM of sub-systems from system 2. Sub-systems from system 5 showed a high GI but also had much higher AVCs than other systems, which lowered the GMs for this system. For wheat, barley and canola, system 5 consistently showed the lowest average GMs whilst those for systems 3 and 4 were similar, but always higher than system 5. The combination of two pasture years with two cropping years (with different crops) was shown to be the most profitable over the long-term.

The input cost for nine different inputs were examined between systems, sub-systems and crops over time and annually. These inputs were fertiliser, weed control, pest control, fungicide, lime, fuel, seed, contractors and repairs and maintenance. The three most prominent input costs were found to be fertiliser, weed control and seed for all sub-systems. The largest proportion of the total input cost was weed control for system 2 and fertiliser for system 5. The fertiliser and weed control costs made up similar proportions of the total input cost for systems 3 and 4. System 5 had higher average total input cost than other systems over the trial period, whilst system 2 usually had the lowest average total input costs. A comparison of the overall average total input cost between crops showed canola to have the highest costs, followed by wheat and then barley. The main input costs for wheat and canola were fertiliser, weed control and seed, but for barley they were fertiliser, weed control and fungicide. When comparing the average total input cost of wheat, barley and canola between sub-systems all three showed similar trends. All three crops from sub-systems belonging to system 5 routinely had higher average total input cost than those from other systems.

The three main input costs – fertiliser, weed control and seed - were then individually examined for each sub-system annually over the 19-year trial period. The average fertiliser costs increased steadily until 2017, after which there was a decrease in costs for all sub-systems, except those from system 5, which continued to increase. The average weed control costs were highest for sub-systems from system 5 and lowest for those from system 2. The sub-systems from system 3 and 4 had similar weed control costs, above those of system 2 but below those of system 5. The same trend was seen for average seed costs. This concluded chapter 5.

Chapter 6 was made up of the conclusion, summary and recommendations taken from the thesis.

6.3) Recommendations

The focus of this thesis was on the long-term sustainability of different short crop rotation systems in the Middle Rûens area of the Overberg. These rotations were managed according to CA principles and the profitability of these systems was assessed as well as the physical/biological and ecological drivers of this profitability. This was aimed at establishing the main drivers of the long-term sustainability of the identified rotation systems. After a few years under CA management, the systems became more resilient to drought – recovering quickly after dry years. Perhaps a similar study should be done for rotation systems in drier areas, such as Riversdale, as different results may be seen in different climatic conditions. This study focused exclusively on short crop rotation systems and not on the livestock aspect of the systems. This may be beneficial to investigate as the integration of livestock into these rotation systems will add to the farm diversity, increasing the resilience, and potentially the profitability, of the farming system as a whole.

A farming system, even when run according to sustainable principles, will not remain sustainable in the long-term without maintained profitability. Therefore, it is essential to also consider economic aspects of a farming system when assessing the long-term sustainability of the system. As seen in this study, input costs are continuously rising and the main factors keeping farming systems profitable are high yields and reduced input levels. However, if a point is reached where there are low yields and input levels remain the same as the prices continue to increase – how will the system remain sustainable? It may be worthwhile to investigate more biologically sustainable methods of farming, such as regenerative agriculture, and whether these methods are economically feasible.

Most farmers in the Overberg use longer rotation systems than the short rotation systems discussed in this study. The typical long rotation systems used are comprised of six years of lucerne pastures followed by six years of cash crops. A study comparing the sustainability of short- and long-term crop rotations may be beneficial to farmers looking for ways to remain sustainable over the long-term.

Finally, additional policy and institutional support for farmers would be helpful as the adoption of CA can be challenging, especially in a financial sense and extra support would assist in convincing more farmers to switch to more sustainable farming methods.

Reference List

Adekalu, K., Olorunfemi, I. & Osunbitan, J. 2007. Grass mulching effect on infiltration, surface runoff and soil loss of three agricultural soils in Nigeria. *Bioresource Technology*. 98(4):912–917.

Agenbag, H. 2007. *Lupin production in the Western Cape and Southern Cape*. [Online], Available: https://www.proteinresearch.net/poems/images/projects/0278/summary/3-1a-pp-agenbag-h-2008.pdf [2020, April 19].

Agricol. 2016. *Lucerne*. [Online], Available: https://www.agricol.co.za/agricol-products/lucerne/ [2020, May 05].

ARC (Agricultural Research Council - Small Grain Institute University of Stellenbosch). 2019. *Production of Small Grains in the Winter Rainfall Area*. [Online], Available: https://www.arc.agric.za/arc-sgi/Documents/2019 Production Guidelines/ARC WINTER ENG 2019.pdf. [2020, May 06].

ARC (Agricultural Research Council). 2020. *Production of small grains in the winter rainfall area*. 2020. Stellenbosch: ARC.

ARC (Agricultural Research Council) Economic & Biometrical Services. 2014. *Assessing the impact of conservation agriculture practices on wheat production in the Western Cape.* 2014. Stellenbosch: University of Stellenbosch.

Barley Requirements. 2021. [Online], Available: https://www.ukmalt.com/uk-malting-industry/barley-requirements/ [2021, July 28].

Basche, A., Archontoulis, S., Kaspar, T., Jaynes, D., Parkin, T. & Miguez, F. 2016. Simulating long-term impacts of cover crops and climate change on crop production and environmnetal outcomes in the Midwestern United States. *Agriculture, Ecosystems & Environment*. 218:95–106.

Basson, C.H. 2017. A financial analysis of different livestock management approaches within different crop rotation systems in the Middle Swartland. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

Bennetzen, E.H., Smith, P. & Porter, J.R. 2016. Agricultural production and greenhouse gas emissions from world regions-The major trends over 40 years. *Global Environmental Change*. 37:43–55.

Clarke, A. 1980. Crop rotations in dryland farming systems. in *International congress on dryland farming* Adelaide, Australia.

Cloete, S., Schoeman, S., Jordaan, G. & Duguma, G. 2002. Genetic parameter estimates of early growth traits in the Tygerhoek Merino flock. *South African Journal of Animal Science*. 32(2):66–75.

Cook, H., Valdes, G. & Lee, H. 2006. Mulch effects on rainfalll interception, soil physical characteristics and temperature under Zea mays L. *Soil and Tillage Research*. 91(1–2):227–235.

Crookes, D. & Strauss, J. 2017. The effect of rainfall variability on sustainable wheat production under no-till farming systems in the Swartland region, South Africa. *African Journal of Agricultural and Resource Economics*. 12(1):62–84.

DAFF. 2010. *Production Guideline for Oats*. Pretoria: Department of Agriculture, Forestry and Fisheries.

DAFF. 2011. *Minor crops of major importance in crop production*. Pretoria: Department of Agriculture, Forestry and Fisheries.

DAFF. 2016a. *Production Guideline for Canola*. Pretoria: Department of Agriculture, Forestry and Fisheries.

DAFF. 2016b. *A Profile of the South African Canola Market Value Chain*. [Online], Available: http://www.nda.agric.za/doaDev/sideMenu/Marketing/AnnualPublications/Commodity Profiles/Livestock/Broiler market value chain profile 2014.pdf. [2020, April 20].

DAFF. 2016c. *A profile of the South African oats market value chain*. Pretoria: Department of Agriculture, Forestry and Fisheries.

DAFF. 2016d. *Production Guideline for Wheat*. [Online], Available: https://www.dalrrd.gov.za/Portals/0/BrochuresandProductionguidelines/Wheat-Production

Guideline.pdf. [2020, 07 May].

DAFF. 2017. *A Profile of the South African Barley Market Value Chain*. [Online], Available: http://www.nda.agric.za/doaDev/sideMenu/Marketing/AnnualPublications/Commodity Profiles/Livestock/Broiler market value chain profile 2014.pdf. [2020, 15 May].

DAFF. 2019. *Abstract of Agricultural Statistics*. [Online], Available: https://www.dalrrd.gov.za/Portals/0/Statistics%20and%20Economic%20Analysis/Statistical%20Information/Abstract%202019.pdf [2020, 12 April].

DAFF. 2020. *Abstract of Agricultural Statistics*. [Online], Available: https://www.dalrrd.gov.za/Portals/0/Statistics%20and%20Economic%20Analysis/Statistical%20Information/Abstract%202020_organized.pdf [2021, 22 February].

Daniel, A.R. 2015. Changes in extreme precipitation events over the central United States in AOGCM-driven regional climate model simulations. Unpublished master's thesis. Iowa: Iowa State Univeristy.

De Kock, G.C. 2012. *Lucerne - King of fodder crops*. [Online], Available: http://gadi.agric.za/articles/Agric/lucerne.php [2020, May 05].

De Lange, J. 2019. *Intake of Grain: 2019/20 Season*. Malmesbury: WesGraan.

Department of Rural Development & Land Reform. 2017. *Sector Plan: Overberg District Rural Development Plan*. [Online], Available: www.overstrand.gov.za [2020, May 25].

Derpsch, R. 2001. Frontiers in Conservation Tillage and Advances in Conservation Practice. Unpublished paper delivered at the 10th International Soil Conservation Organization Meeting. 24-29 May 1999, Purdue University, Indiana, USA.

Derpsch, R. & Friedrich, T. 2010. Sustainable Crop Production Intensification - The Adoption of Conservation Agriculture Worldwide, in *16th ISCO Congress* Santiago, Chile. 23. [Online], Available: http://www.rolf-derpsch.com/sustainablecropproduction.pdf. [2020, 06 May].

Engelbrecht, J.A. 2016. The evaluation of lupins (Lupinus angustifolius) as alternative protein source to soybean oilcake meal in ostrich (Struthio camelus var . domesticus) diets. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

FAO (Food and Agriculture Organisation of the United Nations). 2001. The economics of conservation agriculture. in Rome. [Online], Available: http://www.fao.org/3/y2781e/y2781e03.htm#P0_0 [2020, October 07].

FAO (Food and Agriculture Organisation of the United Nations). 2008. Investing in Sustainable Agricultural Intensification: The Role of Conservation Agriculture - A Framework for Action. in *FAO Technical Workshop* Rome: FAO. [Online], Available:http://www.fao.org/sustainable-food-value-chains/library/details/en/c/266308/ [2020, October 02].

FAO (Food and Agriculture Organisation of the United Nations). 2011. *Save and grow A policymaker's guide to the sustainable intensification of smallholder crop production*. Rome: FAO.

FAO (Food and Agriculture Organisation of the United Nations). 2015. *FINAL REPORT for the International Symposium on Agroecology for Food Security and Nutrition*. 18-19 September, 2014, Rome, Italy.

FAO (Food and Agriculture Organisation of the United Nations). 2018. The Future of Food and Agriculture in *Alternative Pathways to 2050.* Rome, Italy.

FAO (Food and Agriculture Organisation of the United Nations). 2020. *Conservation Agriculture*. [Online], Available: http://www.fao.org/conservation-agriculture/en/ [2021, August 09].

Farooq, M. & Siddique, K. 2015. *Conservation agriculture: concepts, brief history, and impacts on agricultural systems*. Switzerland: Springer International Publishing.

Farooq, M., Flower, K.C., Jabran, K., Wahid, A. & Siddique, K.H.M. 2011. Crop yield and weed management in rainfed conservation agriculture. *Soil and Tillage Research*. 117:172–183.

Findlater, K.M., Kandlikar, M. & Satterfield, T. 2019. Misunderstanding conservation agriculture: Challenges in promoting, monitoring and evaluating sustainable farming. *Environmental Science and Policy*. 100(June 2018):47–54.

Friedrich, T., Derpsch, R. & Kassam, A. 2012. Overview of the Worldwide Spread of Conservation Agriculture Overview of the Worldwide Spread of Conservation Agriculture. *Field Actions Science Reports*. (6):1–7.

Friedrich, T., Kassam, A. & Corsi, S. 2014. Conservation Agriculture in Europe. in *Conservation Agriculture: Global Prospects and Challenges* R.A. Jat, K.L. Sahrawat, & A.H. Kassam (eds.). London: CABI R.A. Jat, K.L. Sahrawat, & A.H. Kassam (eds.). 127–179.

Galal, S. 2021. *Statistics about Agriculture in South Africa*. [Online], Available: https://www.statista.com/map/africa/south-africa/agriculture. [2021, June 08].

Gerland, P., Raftery, A.E., Sevčíková, H., Li, N., Gu, D., Spoorenberg, T., Alkema, L., Fosdick, B.K. 2014. World population stabilization unlikely this century. *Science (New York, N.Y.)*. 346(6206):234.

Gilbert, R. 2018. *South African Barley Concern*. [Online], Available: https://www.internationalmilling.com/south-african-barley-concern/ [2020, May 04].

Giller, K.E., Witter, E., Corbeels, M. & Tittonell, P. 2009. Conservation agriculture and smallholder farming in Africa: the heretics' view. *Field crops research*. 114(1):23–34.

Giller, K.E., Andersson, J.A., Corbeels, M., Kirkegaard, J., Mortensen, D., Erenstein, O. & Vanlauwe, B. 2015. Beyond conservation agriculture. *Frontiers in Plant Science*. 6(870):1–11.

Giraldo, P., Benavente, E., Manzano-Agugliaro, F. & Gimenez, E. 2019. Worldwide research trends on wheat and barley: A bibliometric comparative analysis. *Agronomy*. 9(7).

GreenCape. 2019. *Sustainable Agriculture*. [Online], Available: https://www.greencape.co.za/content/sector/sustainable-agriculture [2020, May 31].

Habig, J., Labuschagne, J., Marais, M., Swart, A. & Claassens, S. 2018. The effect of a medic-wheat rotational system and contrasting degrees of soil disturbance on nematode functional groups and soil microbial communities. *Agriculture, Ecosystems and Environment*. 268(September):103–114.

Hardy, M. 2004. Crop rotation for higher yield. *AgriPROBE*. (September):4–6.

Hardy, M. 2007. Crop rotation for rain-fed crop production. *AgriPROBE*. 4(4):9–17.

Hardy, M., Dziba, L., Kilian, W. & Tolmay, J. 2011. Rainfed Farming Systems in South Africa. in *Rainfed Farming Systems* Springer Science. 395–432.

Herridge, D. 2014. Nitrogen fixation of crop legumes: basic principles and practical management. *Grains Research & Development Corporation*. (July):4.

Hertsgaard, K., Schwarz, P. & Mattern, R. 2008. *Importance of Barley Plumpness and Protein for Malt Quality* . [Online], Available: https://www.ag.ndsu.edu/news/newsreleases/2008/sept-4-2008/importance-of-barley-plumpness-and-protein-for-malt-quality [2021, July 28].

History of Canola Seed Development. 2021. [Online], Available: https://www.canolacouncil.org/canola-encyclopedia/history-of-canola-seed-development/ [2021, July 27].

Hobbs, P.R. 2007. Conservation Agriculture: What is it and why is it important for future sustainable food production. *Journal of Agricultural Science*. (April):1–16.

Hobbs, P.R. & Govaerts, B. 2010. How Conservation Agriculture Can Contribute to Buffering Climate Change. *Climate Change and Crop Production*. 177–199.

Hobbs, P.R. & Gupta, R.K. 2003. Resource-conserving technologies for wheat in the rice-wheat system. in *Improving the productivity and sustainability of rice-wheat systems: issues and impact* 65th ed. J. Ladha, J. Hill, J. Duxbury, R. Gupta, & R. Buresh (eds.). 149–171.

Hobbs, P.R., Sayre, K. & Gupta, R. 2008. The role of conservation agriculture in sustainable agriculture. *Philosophical Transactions of The Royal Society*. 363:543–555.

Hoffmann, W.H. 2001. 'n Finansiële evaluasie van wisselboustelsels vir die Swartland. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

Hoffmann, W.H. 2010. Farm Modelling for Interactive Multidisciplinary Planning of Small Grain Production Systems in South Africa. Unpublished doctoral dissertation. Stellenbosch: Stellenbosch University.

Human, H.J. 2008. Identification of soil and biological factors in crop rotation systems with significance to wheat crop performance in the Overberg production area of South Africa. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

Jat, A., Sahrawat, L., Kassam, A. & Friedrich, T. 2014. *Conservation Agriculture for Sustainable and Resilient Agriculture: Global Status, Prospects and Challenges*. CAB International. [Online], Available: https://www.researchgate.net/publication/267575011_Conservation_Agriculture_for_Sustainable_and_Resilient_Agriculture_Global_Status_Prospects_and_Challenges [2020, October 09].

Jat, R.A., Wani, S.P. & Sahrawat, K.L. 2012. Conservation agriculture in the semi-arid tropics: Prospects and problems. in *Advances in Agronomy* Vol. 117. Academic Press Inc. 191–273.

Jordaan, J. 2002. Cereal Production in Africa with the Focus on South Africa. *Journal of New Seeds*. 4(4):69–81.

Kassam, A., Friedrich, T., Shaxson, F. & Pretty, J. 2009. The spread of conservation agriculture: Justification, sustainability and uptake. *International Journal of Agricultural Sustainability*. 7(4):292–320.

Kassam, A., Friedrich, T., Derpsch, R., Lahmar, R., Mrabet, R., Basch, G., González-Sánchez, E.J. & Serraj, R. 2012. Conservation agriculture in the dry Mediterranean climate. *Field Crops Research*. 132:7–17.

Kassam, A., Friedrich, T. & Derpsch, R. 2018. Global spread of Conservation Agriculture. *International Journal of Environmental Studies*. 76(1):29–51.

Kassie, M. & Tesfaye, K. 2019. Malting Barley Grain Quality and Yield Response to Nitrogen Fertilization in the Arsi Highlands of Ethiopia. *Journal of Crop Science and Biotechnology*. 22(3):225–234.

Kimura, S., Antón, J. & Lethi, C. 2010. Farm Level Analysis of Risk and Risk Management Strategies and Policies Farm Level Analysis of Risk. *Risk Management*. (26).

Knott, S.C. 2015. An analysis of the financial implications of different tillage systems within different crop rotations in the Swartland area of the Western Cape, South Africa. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

Knowler, D. & Bradshaw, B. 2007. Farmers' adoption of conservation agriculture: A review and synthesis of recent research. *Food Policy*. 32(1):25–48.

Koohafkan, P., Basso, B., Findlay, J., Friedrich, T., Jordan, V., Landers, J., Pieri, C., Wall, P. 2001. First world congress on Conservation Agriculture A world-wide challenge. in *First world congress on Conservation Agriculture A world-wide challenge* Madrid. 1–21.

Kooper, P. 2020. Continuous cash crop rotation systems under full CA principles for the Riversdale winter cereal production area. Unpublished master's thesis. Stellenbosch: University of Stellenbosch.

Kuschke, I. & Cassim, A. 2019. *Sustainable Agriculture: 2019 Market Intelligence Report*. Cape Town: GreenCape.

Lal, R. 2006. Enhancing crop yields in the developing countries through restoration of the soil organic carbon pool in agricultural lands. *Land Degradation & Development*. 17:197–209.

Lal, R., Delgado, J., Groffman, P., Millar, N., Dell, C. & Rotz, A. 2011. Management to mitigate and adapt to climate change. *Journal of Soil and Water Conservation*. 66(4):276–285.

Lusse, J. 2016. *Grain quality and grading of wheat*. [Online], Available: https://www.grainsa.co.za/grain-quality-and-grading-of-wheat [2021, July 28].

MacLaren, C., Storkey, J., Strauss, J., Swanepoel, P. & Dehnen-Schmutz, K. 2019. Livestock in diverse cropping systems improve weed management and sustain yields whilst reducing inputs. *Journal of Applied Ecology*. 56(1):144–156.

Macleod, A. 2010. *Undestanding Malting Barley Quality*. [Online], Available: www.bmbri.org [2021, July 28].

Madari, B., Machado, P., Torres, E., Andrade, A. & Valencia, L. 2005. No tillage and crop rotation effects on soil aggregation and organic carbon in a Rhodic Ferralsol from southern Brazil. *Soil & Tillage Research*. 80(1–2):185–200.

Magdoff, F. & Harold, V. 2000. *Building soils for better crops*. Second ed. Burlington: Sustainable Agriculture Network.

MI (Mordor Intelligence). 2020. *South African Alfalfa Hay Market - Growth, Trends and Forecast (2020-2025)*. [Online], Available: https://www.mordorintelligence.com/industry-reports/south-africa-alfalfa-market [2020, May 05].

Modiselle, S. & Verschoor, A.J. 2015. *Western Cape wheat producers and conservation agriculture technology uptake*. [Online], Available: https://www.grainsa.co.za/western-cape-wheat-producers-and-conservation-agriculture-technology-uptake [2020, May 31].

Mudavanhu, S. 2015. The impact of economic policies and instruments on conservation agriculture in South Africa. Unpublished master's thesis. Stellenbosch: University of Stellenbosch. [Online], Available: https://scholar.sun.ac.za. [2020, July 12].

Nell, C.J. 2019. The financial implications of different crop rotation systems for the Goue Rûens. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

NLT (National Lucerne Trust). 2018. *Lucerne Information*. [Online], Available: https://lusern.org/lucerne/lucerne-information/ [2020, May 05].

Nortje, J. 2020. *Local and imported wheat quality reviewed*. [Online], Available: https://sagrainmag.co.za/2020/10/01/local-and-imported-wheat-quality-reviewed/ [2021, July 28].

Panagopoulos, Y., Gassman, P., Arritt, R., Herzmann, D., Campbell, T., Jha, M., Kling, C., Srinivasan, R. 2014. Surface water quality and cropping systems sustainability under a changing climate in the Upper Mississippi River Basin. *Journal of Soil and Water Conservation*. 69(6):483–494.

Partridge, A., Morokong, T. & Sibulali, A. 2020. *Western Cape Agricultural Sector Profile*. [Elsenburg]: Western Cape Department of Agriculture.

Raiesi, F. & Riahi, M. 2014. The influence of grazing exclosure on soil C stocks and dynamics, and ecological indicators in upland arid and semi-arid rangelands. *Ecological Indicators*. 41:145–154.

Reicosky, D.C. 2015. A Looming Collision: Global Population and Food Security. *Journal of Soil and Water Conservation*. 70(5).

Reicosky, D.C., Lindstrom, M.J., Schumacher, T.E., Lobb, D.E. & Malo, D.D. 2005. Tillage-induced CO 2 loss across an eroded landscape. *Soil & Tillage Research*. 81:183–194.

Robertson, M., Holland, J., Cawley, S., Potter, T., Burton, W., Walton, G. & Thomas, G. 2002. Growth and yield differences between triazine-tolerant and non-triazine-tolerant cultivars of canola. *Australian Journal of Agricultural Research*. 53(1):643–651.

Roux, H. & Marais, F. 1996. Breeding Triticale for the South Western Cape. *Triticale: Today and Tomorrow*. 5:669–674.

Sharma, A., Garg, S., Sheikh, I., Vyas, P. & Dhaliwal, H.S. 2020. Effect of wheat grain protein composition on end-use quality. *Journal of Food Science and Technology*. 57(8):2771–2785.

Sihlobo, W. 2018. *The Western Cape is Key to Africa's Canola Production*. [Online], Available: https://wandilesihlobo.com/2018/09/07/the-western-cape-is-key-to-africas-canola-production/ [2020, May 04].

Smit, E. 2019. Utilisation of cover crops: Implications for conservation agriculture systems. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

Smit, H.A., Tolmay, V.L., Barnard, A., Jordaan, J.P., Koekemoer, F.P., Otto, W.M., Pretorius, Z.A., Purchase, J.L. 2010. An overview of the context and scope of wheat (triticum aestivum) research in South Africa from 1983 to 2008. *South African Journal of Plant and Soil*. 27(1):81–96.

Smith, J.D.V., Strauss, J.A. & Hardie, A.G. 2020. Effects of long-term grazed crop and pasture systems under no-till on organic matter fractions and selected quality parameters of soil in the Overberg, South Africa. *South African Journal of Plant and Soil*. 37(1):1–10.

StatsSA. 2020. *Census of Commercial Agriculture 2017*. [Online], Available: http://www.statssa.gov.za/?p=13144 [2020, April 22].

Strauss, J. 2021. Resilient Cropping Systems in a Mediterranean Climate. in *Regenerative Agriculture - What's Missing? What Do We Still Need To Know?* D. Dent & B. Boincean (eds.). Springer. 47–58.

Strauss, J., Hardy, M. & Langenhoven, W. 2012. *Gross margin analysis of crop and pasture production systems within the longterm crop rotation trial at the Tygerhoek Agricultural Research Farm - 2002 to 2010*. [Stellenbosch]: Western Cape Department of Agriculture.

Strauss, J., Swanepoel, P., Laker, M. & Smith, H. 2021. Conservation agriculture in rainfed annual crop production in South Africa. *South African Journal of Plant and Soil*. 1–14.

Swanepoel, C.M., Swanepoel, L.H. & Smith, H.J. 2017. A review of conservation agriculture research in South Africa. *South African Journal of Plant and Soil*. (2017):1–10.

Swart, M. 2013. *All ahead for conservation agriculture*. [Online], Available: https://www.farmersweekly.co.za/crops/field-crops/all-ahead-for-conservation-agriculture/ [2020, May 31].

Tarkalson, D., Hergert, G. & Cassman, G. 2006. Long-Term Effects of Tillage on Soil Chemical Properties and Grain Yields of a Dryland Winter Wheat–Sorghum/Corn–Fallow Rotation in the Great Plains. *Agronomy Journal*. 98:26–33.

Thierfelder, C. & Wall, P.C. 2009. Effects of conservation agriculture techniques on infiltration and soil water content in Zambia and Zimbabwe. *Soil and Tillage Research*. 105(2):217–227.

Thierfelder, C., Amezquita, E.C. & Stahr, K. 2005. Effects of intensifying organic manuring and tillage practices on penetration resistance and infiltration rate. *Soil & Tillage Research*. 82(2):211–226.

Thierfelder, C., Cheesman, S. & Rusinamhodzi, L. 2012. A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Research*. 137:237–250.

Thierfelder, C., Rusinamhodzi, L., Ngwira, A.R., Mupangwa, W., Nyagumbo, I., Kassie, G.T. & Cairns, J.E. 2015. Conservation agriculture in Southern Africa: Advances in knowledge. *Renewable Agriculture and Food Systems*. 30(4):328–348.

Tilman, D. & Clark, M. 2015. Food, agriculture & the environment: Can we feed the world & save the earth? *Daedalus*. 144(4):8–23.

Trenbath, B. 1993. Intercropping for the management of pests and diseases. *Field Crops Research*. 34(3–4):381–405.

Truter, W., Dannhauser, C., Smith, H. & Trytsman, G. 2015. *Conservation agriculture*. [Online], Available: https://www.grainsa.co.za/conservation-agriculture:-part-17 [2021, August 27].

Tygerhoek Research Farm. 2021. [Online], Available: https://www.elsenburg.com/research-farm/tygerhoek-research-farm [2021, August 25].

UN (United Nations). 2020. World population prospects 2020: 10 Key findings. in *Department of Economic & Social Affairs, Population Division*.

Van Der Merwe, J., Cloete, P., Van Schalkwyk, H. & Kleynhans, E. 2016. The Competitive Status of the South African Wheat Industry. *Journal of Economic and Financial Sciences*. 9(3):651–666.

Van Zyl, C., Murdoch, J. & Pienaar, L. 2014. *Western Cape Provincial Profile*. [Cape Town]: Western Cape Department of Agriculture.

Vorster, A.H. 2015. Influence of tillage and cropping sequence on the soil physical properties, water balance and water use efficiency of wheat (Triticum aestivum L.) and canola (Brassica napus) under rainfed-conditions in the Rûens sub-region of the Western Cape. Unpublished master's thesis. Stellenbosch: Stellenbosch University.

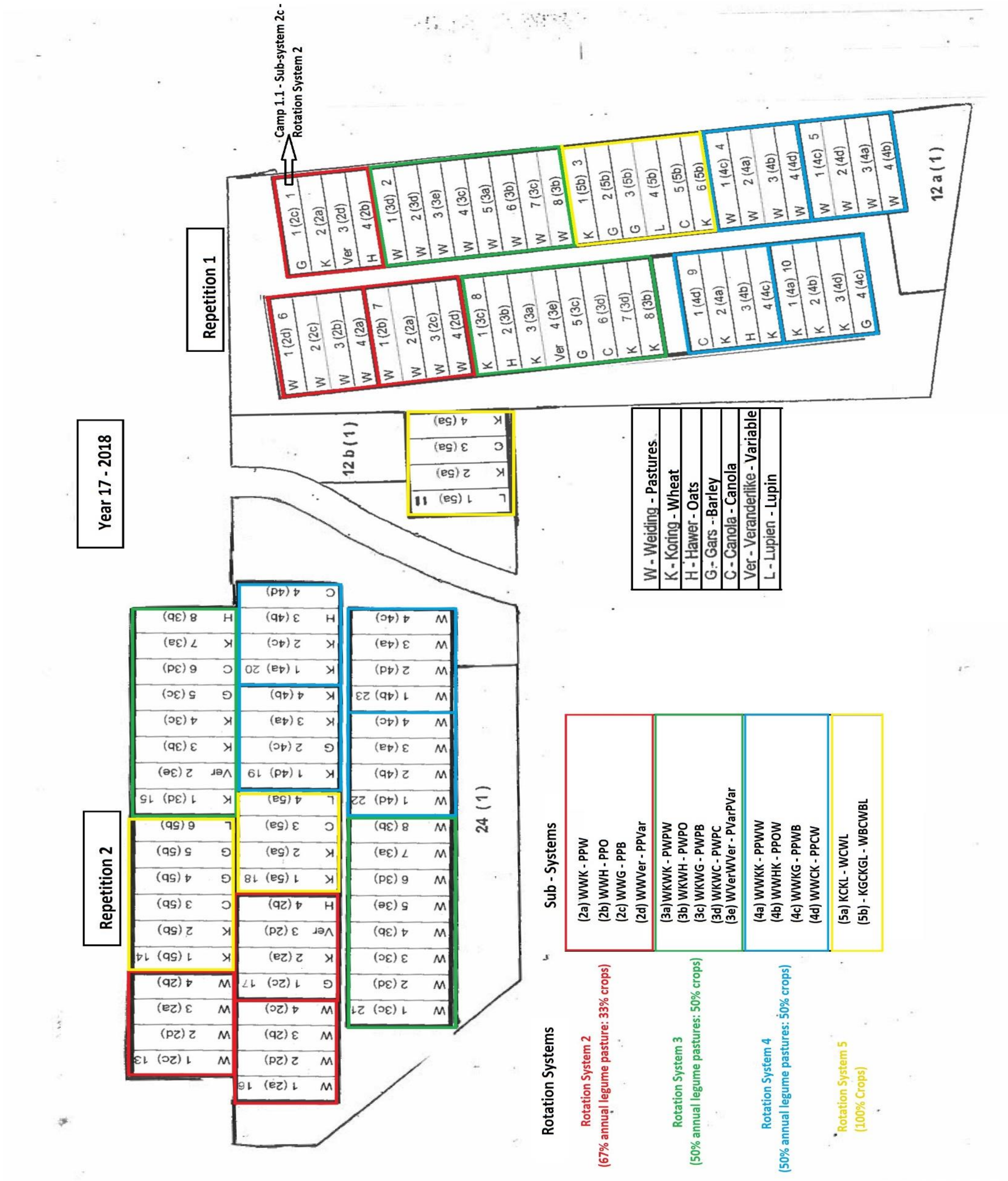
WCDA (Western Cape Department of Agriculture). 2015. *Conservation Agriculture: Promoting climate smart intensification of winter grain production while improving soil health in the Western Cape*. [Online], Available: http://www.greenagri.org.za/assets/documents-/SmartAgri/Case-Studies/2.-Case-Study-CA-FINAL.pdf.

WCDA (Western Cape Department of Agriculture). 2020. *WC AgriStats*. [Online], Available: http://www.elsenburg.com/gis/apps/agristats/ [2020, April 22].

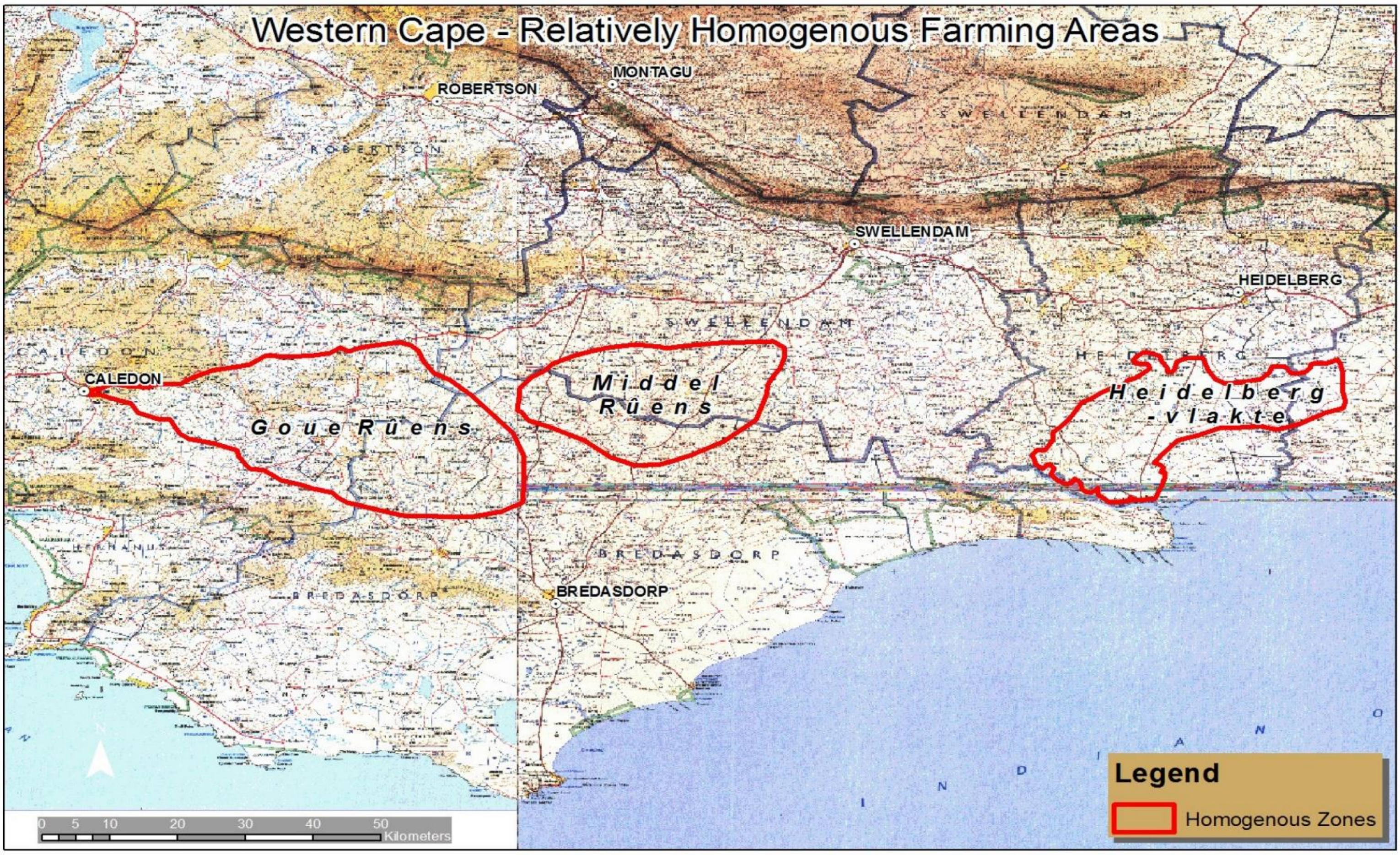
WCG (Western Cape Government). 2020. *Overberg District Municipality*. [Online], Available: https://www.odm.org.za/about-us [2020, May 26].

Winter Cereal Trust. 2021. [Online], Available: https://www.wintercerealtrust.co.za/ [2021, August 26].

Appendix 1 - Layout of Trial Design



Appendix 2 - Map showing the location of the Middle Rûens within the Overberg region



Source: Hoffmann, 2010

Appendix 3 - Rainfall data for Tygerhoek Experimental Farm

	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
Jan	87.9	58.4	7	68.2	77	4.3	41	12.7	4.55	20.77	9.64	10.67	200.9	24.13	39.7	37.1	11.4	10.2	75
Feb	26.8	0	1	17.4	33.2	13.5	45.3	32.24	38.6	57.38	14.66	34.99	31.48	31.72	33.3	10.3	8	28.5	16.6
Mar	4.4	0	14.4	22.4	42	11.6	26	4.56	68.56	26.41	61.19	31.46	38.81	12.69	51.3	6.6	20.1	216.3	25.7
Apr	31	32	29.8	186.2	77.4	21.6	46.1	31.49	25.36	28.65	85.84	32.99	64.45	2.9	15.8	16.8	10.9	7	6.6
May	63.2	36.8	1.8	42.2	44.4	31.3	7.6	21.57	45.16	89.09	39.83	45.18	32.24	0	1.7	14.5	11.8	8.6	31.3
Jun	48.5	14.6	16.6	54.6	24.2	22.8	36.1	79.96	74.07	80.46	136.52	81.97	110.19	91.19	42	39.3	32.3	18.5	38.2
Jul	72.8	11.2	17.6	3.3	83.8	35.7	51.8	73.06	59.4	53.51	78.14	45.67	20.79	0	105.7	43.1	38.1	34.4	35.9
Aug	44	16.2	6.6	26.3	83.3	11.7	36.1	24.86	24.86	52.54	54.09	111.68	10.61	42.3	29.8	63.2	31.3	0.9	69.9
Sep	50.8	24	65.6	0	8.4	9.5	37.7	37.05	32.23	2.53	25.08	14.68	64.98	85.9	73.5	26	55.4	25.5	19
Oct	20.6	25.2	75.6	1.4	16.2	28.9	95	54.31	42.09	25.63	117.4	84.75	25.62	31.2	24.6	0	9.6	29.4	77.9
Nov	19.4	4.2	231.2	54.2	18.2	206.4	81.93	0.75	58.66	75.41	11.64	173.67	47.72	36.2	10.1	0	24.6	0	0
Dec	13.2	296	236.4	7.2	17.2	72.4	73.65	11.92	24.32	0.28	14.72	3.56	25.34	0.41	21	0	24.9	0	0
Annual Average	40.2	43.2	58.6	40.3	43.8	39.1	48.2	32.0	41.5	42.7	54.1	55.9	56.1	29.9	37.4	21.4	23.2	31.6	33.0
Annual Total	483	519	704	483	525	470	578	384	498	513	649	671	673	359	449	257	278	379	396
Growing Season (Apr – Sept)	310	135	138	313	322	133	215	268	261	307	420	332	303	222	269	203	180	95	201